American College of Radiology
ACR Appropriateness Criteria®
Thoracoabdominal Aortic Aneurysm or Dissection: Treatment Planning and Follow-Up

Variant 1: **Follow-up of known thoracoabdominal aortic aneurysm or dissection without repair. Without or with new symptoms.**

Procedure	Appropriateness Category	Relative Radiation Level
MRA chest abdomen pelvis without and with IV contrast	Usually Appropriate	O
MRA chest abdomen pelvis without IV contrast	Usually Appropriate	O
CTA chest abdomen pelvis with IV contrast	Usually Appropriate	☢☢☢☢☢
MRA chest and abdomen without and with IV contrast	May Be Appropriate	O
MRA chest and abdomen without IV contrast	May Be Appropriate	O
CT chest abdomen pelvis with IV contrast	May Be Appropriate	☢☢☢☢
CT chest abdomen pelvis without and with IV contrast	May Be Appropriate	☢☢☢☢
CT chest abdomen pelvis without IV contrast	May Be Appropriate	☢☢☢☢
CT chest and abdomen with IV contrast	May Be Appropriate	☢☢☢☢
CT chest and abdomen without and with IV contrast	May Be Appropriate	☢☢☢☢
CTA chest and abdomen with IV contrast	May Be Appropriate	☢☢☢☢
US duplex Doppler aorta abdomen	Usually Not Appropriate	O
US echocardiography transthoracic resting	Usually Not Appropriate	O
Radiography chest	Usually Not Appropriate	☢
Radiography chest abdomen pelvis	Usually Not Appropriate	☢☢☢
Aortography chest abdomen pelvis	Usually Not Appropriate	☢☢☢☢
CT chest and abdomen without IV contrast	Usually Not Appropriate	☢☢☢☢

Variant 2: **Planning for endovascular or open repair of thoracoabdominal aorta aneurysm or dissection.**

Procedure	Appropriateness Category	Relative Radiation Level
MRA chest abdomen pelvis without and with IV contrast	Usually Appropriate	O
MRA chest abdomen pelvis without IV contrast	Usually Appropriate	O
CTA chest abdomen pelvis with IV contrast	Usually Appropriate	☢☢☢☢☢
MRA chest and abdomen without and with IV contrast	May Be Appropriate (Disagreement)	O
CT chest abdomen pelvis with IV contrast	May Be Appropriate (Disagreement)	☢☢☢☢
CT chest abdomen pelvis without and with IV contrast	May Be Appropriate (Disagreement)	☢☢☢☢
CTA chest and abdomen with IV contrast	May Be Appropriate (Disagreement)	☢☢☢☢
US duplex Doppler aorta abdomen	Usually Not Appropriate	O
US echocardiography transthoracic resting	Usually Not Appropriate	O
Radiography chest	Usually Not Appropriate	☢
Radiography chest abdomen pelvis	Usually Not Appropriate	☢☢☢
Aortography chest abdomen pelvis	Usually Not Appropriate	☢☢☢☢
MRA chest and abdomen without IV contrast	Usually Not Appropriate	O
CT chest abdomen pelvis without IV contrast	Usually Not Appropriate	☢☢☢☢
CT chest and abdomen with IV contrast	Usually Not Appropriate	☢☢☢☢
CT chest and abdomen without and with IV contrast	Usually Not Appropriate	☢☢☢☢
CT chest and abdomen without IV contrast	Usually Not Appropriate	☢☢☢☢

Variant 3: **Follow-up after endovascular repair of thoracoabdominal aortic aneurysm or dissection.**

Procedure	Appropriateness Category	Relative Radiation Level
MRA chest abdomen pelvis without and with IV contrast	Usually Appropriate	O
CTA chest abdomen pelvis with IV contrast	Usually Appropriate	☢☢☢☢☢
Aortography chest abdomen pelvis	May Be Appropriate (Disagreement)	☢☢☢☢
MRA chest abdomen pelvis without IV contrast	May Be Appropriate	O
MRA chest and abdomen without and with IV contrast	May Be Appropriate (Disagreement)	O
MRA chest and abdomen without IV contrast	May Be Appropriate	O
CT chest abdomen pelvis with IV contrast	May Be Appropriate	☢☢☢☢
CT chest abdomen pelvis without and with IV contrast	May Be Appropriate	☢☢☢☢
CT chest abdomen pelvis without IV contrast	May Be Appropriate	☢☢☢☢
CTA chest and abdomen with IV contrast	May Be Appropriate (Disagreement)	☢☢☢☢
US duplex Doppler aorta abdomen	Usually Not Appropriate	O
US echocardiography transthoracic resting	Usually Not Appropriate	O
Radiography chest	Usually Not Appropriate	☢
Radiography chest abdomen pelvis	Usually Not Appropriate	☢☢☢
CT chest and abdomen with IV contrast	Usually Not Appropriate	☢☢☢☢
CT chest and abdomen without and with IV contrast	Usually Not Appropriate	☢☢☢☢
CT chest and abdomen without IV contrast	Usually Not Appropriate	☢☢☢☢

<u>Variant 4:</u> **Follow-up after open repair of thoracoabdominal aortic aneurysm or dissection.**

Procedure	Appropriateness Category	Relative Radiation Level
MRA chest abdomen pelvis without and with IV contrast	Usually Appropriate	O
CTA chest abdomen pelvis with IV contrast	Usually Appropriate	☢☢☢☢☢
MRA chest abdomen pelvis without IV contrast	May Be Appropriate	O
MRA chest and abdomen without and with IV contrast	May Be Appropriate	O
MRA chest and abdomen without IV contrast	May Be Appropriate	O
CT chest abdomen pelvis with IV contrast	May Be Appropriate	☢☢☢☢
CT chest abdomen pelvis without and with IV contrast	May Be Appropriate	☢☢☢☢
CT chest abdomen pelvis without IV contrast	May Be Appropriate	☢☢☢☢
CT chest and abdomen with IV contrast	May Be Appropriate	☢☢☢☢
CT chest and abdomen without and with IV contrast	May Be Appropriate	☢☢☢☢
CTA chest and abdomen with IV contrast	May Be Appropriate	☢☢☢☢
US duplex Doppler aorta abdomen	Usually Not Appropriate	O
US echocardiography transthoracic resting	Usually Not Appropriate	O
Radiography chest	Usually Not Appropriate	☢
Radiography chest abdomen pelvis	Usually Not Appropriate	☢☢☢
Aortography chest abdomen pelvis	Usually Not Appropriate	☢☢☢☢
CT chest and abdomen without IV contrast	Usually Not Appropriate	☢☢☢☢

THORACOABDOMINAL AORTIC ANEURYSM OR DISSECTION: TREATMENT PLANNING AND FOLLOW-UP

Expert Panels on Vascular Imaging and Interventional Radiology: Benjamin N. Contrella, MD[a]; Minhajuddin S. Khaja, MD, MBA[b]; Bill S. Majdalany, MD[c]; Charles Y. Kim, MD[d]; Sanjeeva P. Kalva, MD[e]; Adam W. Beck, MD[f]; William F. Browne, MD[g]; Rachel E. Clough, MD, PhD[h]; Maros Ferencik, MD, PhD, MCR[i]; Fernando Fleischman, MD[j]; Andrew J. Gunn, MD[k]; Sean M. Hickey, MD[l]; Asha Kandathil, MD[m]; Karen M. Kim, MD[n]; Eric J. Monroe, MD[o]; Cassius Iyad Ochoa Chaar, MD, MS[p]; Matthew J. Scheidt, MD[q]; Amanda R. Smolock, MD, PhD[r]; Scott D. Steenburg, MD[s]; Kathleen Waite, MD[t]; Jason W. Pinchot, MD[u]; Michael L. Steigner, MD.[v]

<u>Summary of Literature Review</u>

Introduction/Background

Aortic pathologies including aneurysm and dissection, among others, commonly involve the thoracic and abdominal aorta, thereby requiring evaluation of the entirety of the aorta. Thoracoabdominal aortic aneurysms (TAAAs), defined as enlargement of the descending thoracic aorta to 1.5 times the normal diameter with extension into the abdominal aorta, are typically discovered incidentally on cross-sectional imaging of the chest or abdomen. However, a minority of patients may present with an acute aortic syndrome if enlargement is due to acute dissection of the aorta or aortic rupture. As with most aortic pathologies excluding trauma, enlargement of the thoracoabdominal aorta, whether due to aneurysm or dissection, is increasingly common with age and most commonly seen in those ≥65 of age. The underlying pathology resulting in enlargement varies widely but may be due to atherosclerotic disease, connective tissue disorders, vasculitis, or, rarely, infection. Although multiple systems of classification based on anatomic extent exist, the Crawford system is the most widely used, and the extent of the aneurysm and involvement of aortic branch vessels has a significant impact on treatment. Although aneurysms or dissections with thoracic or abdominal aorta diameter of ≤5.5 cm are typically managed medically and with serial imaging, aortas larger than these measurements may require surgical or endovascular treatment [1,2].

Aortic dissections are the results of a disruption in the aortic wall with blood flow into the media resulting in a true and false lumen, which may propagate antegrade or retrograde. Aortic dissections are classified by acuity, anatomic location of entry tear, extent of false lumen, and presence or absence of complicating features. The Stanford classification is commonly used to categorize aortic dissections. Type A dissection involves the ascending aorta (and may extend distally), and type B dissection is limited to the aortic arch and descending thoracic aorta. Complicating features include cerebral, coronary, and/or visceral malperfusion syndrome as well as rupture. Aortic dissections may require emergent surgical repair, thoracic endovascular aortic repair (EVAR), or other endovascular interventions to treat malperfusion syndromes following initial medical therapies. Aneurysmal expansion of the false lumen occurs in up to 50% of patients requiring follow-up imaging.

Traditionally, treatment for thoracoabdominal aneurysm or dissection has been surgical. Although surgical repair demonstrated a survival benefit over medical management, open TAAA repair carries high mortality and morbidity risks [3-5]. A 2016 analysis of outcomes of more than 3,000 TAAA repairs reports an operative mortality rate of 7.5%, with permanent paraplegia in 2.9%, permanent renal failure in 5.7%, and stroke in 2.2% for a total composite rate of an adverse event of 14.4% [3]. Over the past 10 to 20 years, alternative treatment regimens have been

[a]Research Author, Allegheny Health Network, Pittsburgh, Pennsylvania. [b]University of Michigan, Ann Arbor, Michigan. [c]Panel Chair, University of Vermont Medical Center, Burlington, Vermont. [d]Panel Chair, Duke University Medical Center, Durham, North Carolina. [e]Panel Vice-Chair, Massachusetts General Hospital, Boston, Massachusetts. [f]University of Alabama at Birmingham Medical Center, Birmingham, Alabama; Society for Vascular Surgery. [g]Weill Cornell Medicine, New York, New York. [h]St Thomas' Hospital, King's College, School of Biomedical Engineering and Imaging Science, London, United Kingdom; Society for Cardiovascular Magnetic Resonance. [i]Knight Cardiovascular Institute, Oregon Health & Science University, Portland, Oregon; Society of Cardiovascular Computed Tomography. [j]Keck School of Medicine of USC, Los Angeles, California; American Association for Thoracic Surgery. [k]University of Alabama at Birmingham, Birmingham, Alabama. [l]David Geffen School of Medicine, University of California Los Angeles, Los Angeles, California; American College of Emergency Physicians. [m]UT Southwestern Medical Center, Dallas, Texas; Commission on Nuclear Medicine and Molecular Imaging. [n]University of Michigan, Ann Arbor, Michigan; The Society of Thoracic Surgeons. [o]University of Wisconsin, Madison, Wisconsin. [p]Yale University School of Medicine, New Haven, Connecticut; Society for Vascular Surgery. [q]Froedtert & The Medical College of Wisconsin, Milwaukee, Wisconsin. [r]Froedtert & The Medical College of Wisconsin, Milwaukee, Wisconsin. [s]Indiana University School of Medicine and Indiana University Health, Indianapolis, Indiana; Committee on Emergency Radiology-GSER. [t]Duke University Medical Center, Durham, North Carolina, Primary care physician. [u]Specialty Chair, University of Wisconsin, Madison, Wisconsin. [v]Specialty Chair, Brigham & Women's Hospital, Boston, Massachusetts.

Reprint requests to: publications@acr.org

developed for some patient groups including hybrid repair and entirely endovascular repair. In hybrid repair, a combination of surgical and endovascular techniques is used, often in a staged format, with techniques including abdominal debranching followed by thoracic endovascular repair. Hybrid repairs showed favorable results in several series, although with aortic related mortality rates of 9%, 14%, and 14% at 1, 2, and 5 years, respectively, in one study [6-8].

More recently, a number of endovascular techniques have been used for repair, including thoracic EVAR, EVAR with parallel (eg, chimney/snorkel) stents into the branch artery, fenestrated EVAR, and branched EVAR [9-12]. Multiple studies have found encouraging results in terms of technical success, intraprocedural mortality, and branch vessel patency, although with high rates of reintervention for endoleaks [10,13-16]. Similarly, techniques for endovascular treatment of type B dissection have also been refined over the past decades, with new innovations in treating type A dissection emerging as well. The decision of surgical versus hybrid or endovascular repair is based on the characteristics of the aneurysm or dissection, along with factors such as suitability for surgery and patient preference. Regardless of type of treatment, postprocedural surveillance is important because patients with poor compliance with follow-up imaging are found to have higher rates of aortic rupture [17].

For information on interventional planning and follow-up of thoracic aortic aneurysm or abdominal aortic aneurysm (AAA), please see the ACR Appropriateness Criteria® topics on "Thoracic Aorta Interventional Planning and Follow-Up"[1] and "Abdominal Aortic Aneurysm: Interventional Planning and Follow-Up" [2]. For information on AAA follow-up please see the ACR Appropriateness Criteria® topic on "Abdominal Aortic Aneurysm Follow-Up (Without Repair)" [18].

Special Imaging Considerations

As MRI technology and sequences have continued to improve, multiple new sequences and protocols have been developed for assessment of the aorta. In particular, sequences aimed at evaluating flow dynamics and aortic wall stress have been used to predict aneurysm growth [19-24]. Other authors have advocated for the use of superparamagnetic iron oxide given intravenously to assess for inflammatory changes in the aortic wall [25,26]. Continued innovation has allowed advancement in sequences and techniques such as 4-D MRI for evaluation of TAAA or dissection, most commonly used at academic institutions.

Discussion of Procedures by Variant

Variant 1: Follow-up of known thoracoabdominal aortic aneurysm or dissection without repair. Without or with new symptoms.

Aortography Chest Abdomen Pelvis

Aortogram with digital subtraction angiography (DSA) for evaluation of the thoracic and abdominal aorta has a sensitivity of up to 90% and a specificity of 95% for acute aortic pathology [27]. Although it has the advantage of allowing immediate intervention if an abnormality is identified, aortography is an invasive procedure that is now typically performed for treatment after diagnosis of a new or worsening aortic pathology. Additionally, a 2003 study comparing MR angiography (MRA) with angiography suggested increased accuracy of MRA in assessing vessel diameter: a key component of follow-up for TAAA or dissection [28].

CT Chest, Abdomen, and Pelvis With IV Contrast

There is no relevant literature regarding venous phase CT chest, abdomen, and pelvis for the follow-up of known thoracoabdominal aneurysm or dissection, because most follow-up imaging for known dissection or aneurysm uses an arterially timed contrast bolus in the form of a CT angiography (CTA) (discussed below). However, contrast-enhanced CT can provide information regarding the size and extent of aortic pathology as well as evaluate for extravascular pathology. If venous phase or unenhanced CT has already been performed, additional imaging with CTA may not be required in some patients.

CT Chest, Abdomen, and Pelvis Without and With IV Contrast

There is no relevant literature regarding venous phase CT chest, abdomen, and pelvis for the follow-up of known thoracoabdominal aneurysm or dissection because most follow-up imaging for known dissection or aneurysm uses an arterially timed contrast bolus in the form of a CTA (discussed below). However, contrast-enhanced CT can provide information regarding the size and extent of aortic pathology as well as evaluate for extravascular pathology.

Although typically not performed for the purpose of follow-up of thoracoabdominal aortic pathology, multiphase CT performed to evaluate for extravascular pathology can often assess for acute changes in thoracoabdominal dissection or aneurysm, such as intramural hematoma. Unenhanced CT may be able to delineate extravascular complications such as hemorrhage or rupture. If venous phase or unenhanced CT has already been performed, additional imaging with CTA may not be required in some patients.

CT Chest, Abdomen, and Pelvis Without IV Contrast

There is no relevant literature for CT chest, abdomen, and pelvis without intravenous (IV) contrast for the follow-up of known thoracoabdominal aneurysm or dissection. Although most follow-up of known aortic disease is performed with IV contrast [29-31], select groups of patients may be monitored with unenhanced CT to evaluate measurements of aortic size, which may guide further management [32]. Unenhanced CT may be able to delineate extravascular complications such as hemorrhage or rupture [32]. If venous phase or unenhanced CT has already been performed, additional imaging with CTA may not be required in some patients.

CT Chest and Abdomen With IV Contrast

There is no relevant literature regarding venous phase CT chest and abdomen for the follow-up of known thoracoabdominal aneurysm or dissection because most follow-up imaging uses an arterially timed contrast bolus in the form of a CTA (discussed below). Compared with CT of the chest, abdomen, and pelvis, exclusion of the pelvis may result in incomplete evaluation of the extent of aortic pathology. If venous phase or unenhanced CT has already been performed, additional imaging with CTA may not be required in some patients.

CT Chest and Abdomen Without and With IV Contrast

There is no relevant literature regarding CT chest and abdomen without and with IV contrast for the follow-up of known thoracoabdominal aneurysm or dissection because most follow-up imaging uses an arterially timed contrast bolus in the form of a CTA (discussed below). Compared with CT of the chest, abdomen, and pelvis, exclusion of the pelvis may result in incomplete evaluation of the extent of aortic pathology. If venous phase or unenhanced CT has already been performed, additional imaging with CTA may not be required in some patients.

CT Chest and Abdomen Without IV Contrast

There is no relevant literature regarding CT chest and abdomen without IV contrast for the follow-up of known thoracoabdominal aneurysm or dissection because most follow-up imaging uses an arterially timed contrast bolus in the form of a CTA. Compared with CT of the chest, abdomen, and pelvis, exclusion of the pelvis may result in incomplete evaluation of the extent of aortic pathology. If venous phase or unenhanced CT has already been performed, additional imaging with CTA may not be required in some patients.

CTA Chest, Abdomen, and Pelvis With IV Contrast

CTA of the chest, abdomen, and pelvis with IV contrast uses fast acquisition times to allow for rapid evaluation of the aorta and diagnosis of pathology. Fast acquisition times are particularly valuable in patients with known TAAA or dissection with new symptoms, given the high acuity of these conditions in the event of disease extension or worsening. The precise and reproducible measurements of the aorta with CTA are valuable for monitoring aortic growth and interval changes [33,34]. Electrocardiographically (ECG)-gated or triggered CTA is an additional option that can be used to evaluate the ascending aorta in patients with concern for conversion of a dissection into a type A dissection or for aneurysmal enlargement of the ascending aorta. With ECG gating, artifact from aortic pulsation is reduced and maximum interobserver variability of 1.2 mm in the ascending aorta has been reported, emphasizing the reproducibility of CTA [31,34].

Acquisition of thin axial slices with subsequent 3-D reconstruction along with homogenous luminal opacification allows for precise measurements and assessment of aortic anatomy, using postprocessing software for vessel analysis. Along with low interobserver variability, this allows for an excellent ability to detect changes in the aortic diameter or extent of dissection [31,33,34]. Furthermore, CTA can readily detect complications including thoracoabdominal aneurysm rupture or dissection extension causing malperfusion of the supra-aortic branch vessels, mesenteric arteries, renal arteries, lower extremities, or coronary arteries [31,35]. CTA has also been used in certain situations to predict enlargement of saccular aneurysms using flow dynamics [36].

Compared with CTA of the chest and abdomen, imaging of the pelvis carries the benefit of evaluation of the iliofemoral vessels to evaluate the extent of dissection or aneurysmal dilatation and suitability for possible endovascular intervention.

CTA Chest and Abdomen With IV Contrast
Compared with CTA of the chest, abdomen, and pelvis, the lack of visualization of the iliofemoral vessels precludes evaluation for suitability for possible endovascular intervention or for aneurysm dilation/dissection of the iliac or femoral arteries if pathology extends to the bifurcation.

MRA Chest, Abdomen, and Pelvis Without and With IV Contrast
Similar to CTA, MRA of the thoracoabdominal aorta allows for precise and reproducible assessment or aortic sac size in aneurysm or extent of dissection in thoracoabdominal aortic dissection [33,37-39]. In patients with new symptoms, MRI has conventionally been used as a secondary imaging modality because of relatively long imaging times [40]. However, MRI can be used to accurately assess for acute aortic pathology in this clinical setting [40-42].

Use of a contrast agent in MRA allows for 4-D evaluation of flow dynamics, with acquisition of multiple time-points allowing for detailed evaluation of flow dynamics associated with aortic aneurysm or dissection [43]. This can be used with a variety of unenhanced MRA techniques such as time-of-flight and phase-contrast imaging that can also allow for evaluation of aortic dissection and aneurysm [44,45]. Similar to CTA, ECG gating can be used for a more accurate assessment of the ascending thoracic aorta if concern exists for retrograde extension of pathology [46,47]. MRA can allow for the evaluation of aortic valve dysfunction associated with ascending aortic dilation or dissection, which cannot typically be identified on CTA [33,46,47].

MRI also allows evaluation for extravascular pathology. In a 2014 study, more than 80% of patients had at least one extravascular finding, with 6.4% found to have a major extravascular finding including neoplasm, spine infection, or pericardial effusion [48].

A 2018 comparative study with 45 patients divided into noncontrast-enhanced and blood pool contrast groups was performed to qualitatively and quantitatively evaluate image quality as well as reproducibility [47]. This study concluded that IV contrast allows for higher quality imaging with more reproducible and accurate vessel measurements [47]. The findings were consistent with a 2010 study supporting the use of IV contrast for vascular detail [49]. In contrast to these findings, however, multiple other studies have found similar accuracy and reproducibility in assessing vessel diameter between contrast- and noncontrast-enhanced MRI studies [44,50,51].

MRA Chest, Abdomen, and Pelvis Without IV Contrast
Multiple unenhanced MRA techniques such as time-of-flight, phase-contrast imaging, and steady-state free precision (SSFP) have been developed that allow for the evaluation of aortic dissection and aneurysm [44,45]. Even without IV contrast, MRA can be used to precisely evaluate the thoracoabdominal aorta size, as well as for access vessel size, intraluminal thrombus, and branch vessel involvement [37,39]. A 2017 observational study comparing AAA measurements in CTA and noncontrast MRA showed strong agreement, with intraclass coefficient >0.99 and interobserver reproducibility >0.99 for both CTA and MRA [45]. This study also noted a potential benefit of noncontrast MRA allowing evaluation of the composition of intraluminal thrombus, potentially allowing for risk quantification for disease progression [45]. This finding was also supported by a follow-up 2019 article [52].

Although some studies have shown more accurate measurements with contrast-enhanced MRA compared with noncontrast MRA, other studies have shown an equal ability to detect aortic pathology and to measure aortic size [44,50,51]. A 2014 study comparing thoracic aortic measurements and pathology in 76 patients undergoing both contrast- and noncontrast-enhanced MRA showed high agreement between study types, with low intra- and interobserver dependency (intraclass correlation coefficient 0.99) [51]. A similar 2017 study comparing thoracic aorta measurements/findings on contrast- and noncontrast-enhanced MRA performed on a group of 50 patients favored noncontrast-enhanced MRA over contrast-enhanced MRA as the technique of choice because of superior image quality and better vessel sharpness in the ascending aorta [44]. Although these existing studies focus on the thoracic or abdominal segments of the aorta rather than the thoracoabdominal aorta, findings can likely be extrapolated to the thoracoabdominal aorta.

MRA Chest and Abdomen Without and With IV Contrast
Compared with MRA of the chest, abdomen, and pelvis, exclusion of the pelvis carries the benefit of faster acquisition time. However, extension to the abdomen without the pelvis involved, results in limited evaluation of the iliofemoral vessels to evaluate suitability for possible endovascular intervention or for aneurysm dilation/dissection of the iliac or femoral arteries if pathology extends to the bifurcation.

MRA Chest and Abdomen Without IV Contrast

Compared with MRA of the chest, abdomen, and pelvis, exclusion of the pelvis carries the benefit of faster acquisition time. However, extension to the abdomen without inclusion of the pelvis involved results in limited evaluation of the iliofemoral vessels to evaluate suitability for possible endovascular intervention or for aneurysm dilation/dissection of the iliac or femoral arteries if pathology extends to the bifurcation.

Radiography Chest

Chest radiographs demonstrate abnormalities in a large percentage of patients with acute thoracoabdominal pathology. Most commonly, a widened mediastinum is appreciated in patients with pathology extending to the proximal to mid thoracic aorta, and a posteroanterior (PA) projection is found to be significantly more accurate than an anteroposterior (AP) projection [53]. Other studies have found that a chest radiograph is not sensitive (64%) or specific (87%) for thoracic aortic disease [54,55]. Given the relatively low sensitivity and specificity, chest radiography should not substitute for cross-sectional imaging. Furthermore, the role of chest radiography in the follow-up of known thoracoabdominal disease is limited because radiographs would be unlikely to appreciate subtle changes in aortic size.

Radiography Chest, Abdomen, and Pelvis

There is no relevant literature for chest, abdomen, and pelvis radiographs for the follow-up of thoracoabdominal aortic dissection or aneurysm.

Chest radiographs demonstrate abnormalities in a large percentage of patients with acute thoracoabdominal pathology. Most commonly, a widened mediastinum is appreciated in patients with pathology extending to the proximal to mid thoracic aorta, and a PA projection is found to be significantly more accurate than an AP projection [53]. Other studies have found that a chest radiograph is not sensitive (64%) or specific (87%) for thoracic aortic disease [54,55]. Given the relatively low sensitivity and specificity, chest radiography should not substitute for cross-sectional imaging. Furthermore, the role of chest radiography in the follow-up of known thoracoabdominal disease is limited because radiographs would be unlikely to appreciate subtle changes in aortic size.

US Duplex Doppler Aorta Abdomen

Duplex ultrasound (US) of the abdominal aorta is an option for evaluation of the thoracoabdominal aorta, although the ability to evaluate the aorta above the diaphragm may be markedly limited by acoustic windows. Prior studies comparing US, CT, and MRI of the abdominal aorta found that US is a reliable method to diagnose and follow AAAs [56]. In the evaluation of thoracoabdominal aortic dissection, US can also be used to evaluate blood flow in the true and false lumens and to directly and dynamically monitor the motion of dissection flaps [43]. As such, abdomen US can be performed serially to evaluate for aortic size changes or dissection hemodynamic changes. However, a limited ability to evaluate the thoracic aorta due to difficult acoustic windows could result in poor image quality or the inability to view changes to the aorta.

US Echocardiography Transthoracic Resting

Transthoracic echocardiogram (TTE) allows visualization of the heart and portions of the thoracic aorta. TTE can be used to evaluate the heart for complications such as pericardial effusion in patients with new symptoms [57]. However, portions of the proximal descending thoracic aorta may be poorly visualized with TTE because of patient acoustic windows and habitus, creating the possibility of false-negative examinations in patients with new symptoms [58]. These characteristics have resulted in a low sensitivity of 31% to 55% for the diagnosis of acute type B aortic dissection on TTE [33]. TTE is also limited by the ability to visualize the abdominal aorta to determine the extent of thoracoabdominal aortic pathology.

Variant 2: Planning for endovascular or open repair of thoracoabdominal aorta aneurysm or dissection.

Aortography Chest Abdomen Pelvis

There is no relevant literature regarding aortography for the planning of thoracoabdominal aortic endovascular or open repair. Aortogram with DSA for evaluation of the thoracic and abdominal aorta has a sensitivity of up to 90% and a specificity of 95% for acute aortic syndrome [27]. The role of aortography before endovascular or open repair is limited to noninvasive modalities such as CTA and MRA. Furthermore, the projectional nature of catheter angiograms limits its ability to evaluate the 3-D configuration of vessels, increasing the risk of error if procedures are planned based on angiogram [59].

CT Chest, Abdomen, and Pelvis With IV Contrast
There is no relevant literature for venous phase CT chest, abdomen, and pelvis for the planning of thoracoabdominal aortic endovascular or open repair. Most preprocedural CT imaging for thoracoabdominal pathology uses an arterially timed contrast bolus in the form of a CTA (discussed below). Although typically not performed for the purpose of procedural planning, contrast-enhanced CT performed to evaluate for extravascular pathology can often assess for acute changes in thoracoabdominal dissection or aneurysm. If venous phase or unenhanced CT has already been performed, additional imaging with CTA may not be required in some patients but may be needed for preprocedure sizing and evaluation of pathology.

CT Chest, Abdomen, and Pelvis Without and With IV Contrast
There is no relevant literature for venous phase CT chest, abdomen, and pelvis with noncontrast phase for the planning of thoracoabdominal aortic endovascular or open repair. Most preprocedural CT imaging for thoracoabdominal pathology uses an arterially timed contrast bolus in the form of a CTA (discussed below). Although typically not performed for the purpose of procedural planning, contrast-enhanced CT performed to evaluate for extravascular pathology can often assess for acute changes in thoracoabdominal dissection or aneurysm. If venous phase or unenhanced CT has already been performed, additional imaging with CTA may not be required in some patients but may be needed for preprocedure sizing and evaluation of pathology.

CT Chest, Abdomen, and Pelvis Without IV Contrast
There is no relevant literature for CT chest, abdomen, and pelvis without IV contrast for the planning of thoracoabdominal aortic endovascular or open repair. CT without IV contrast would likely be able to assess aortic size and for nonvascular findings, but utility for preprocedure planning would be markedly limited in the absence of IV contrast. If venous phase or unenhanced CT has already been performed, additional imaging with CTA may not be required in some patients but may be needed for preprocedure sizing and evaluation of pathology.

CT Chest and Abdomen With IV Contrast
There is no relevant literature for venous phase CT chest and abdomen for the planning of thoracoabdominal aortic endovascular or open repair. Compared with CT of the chest, abdomen, and pelvis, exclusion of the pelvis from the field of view carries the drawback of precluding evaluation of the iliofemoral access vessels if endovascular repair is considered. Furthermore, if the thoracoabdominal dissection or aneurysm extends into the pelvis, a lack of pelvis evaluation could result in incomplete evaluation of the aortic pathology. In select cases with recent imaging of the pelvis or in cases of planned open repair without extension into the pelvic vasculature, further imaging of the pelvis vasculature may not be needed. If venous phase or unenhanced CT has already been performed, additional imaging with CTA may not be required in some patients but may be needed for preprocedure sizing and evaluation of pathology.

CT Chest and Abdomen Without and With IV Contrast
There is no relevant literature for venous phase CT chest and abdomen with noncontrast phase for the planning of thoracoabdominal aortic endovascular or open repair. Most preprocedural CT imaging for thoracoabdominal pathology uses an arterially timed contrast bolus in the form of a CTA (discussed below). Although typically not performed for the purpose of procedural planning, contrast-enhanced CT performed to evaluate for extravascular pathology can often assess for acute changes in thoracoabdominal dissection or aneurysm. However, exclusion of the pelvis from the field of view carries the drawback of precluding evaluation of the iliofemoral access vessels if endovascular repair is considered. Furthermore, if the thoracoabdominal dissection or aneurysm extends into the pelvis, lack of pelvis evaluation could result in incomplete evaluation of the aortic pathology. In select cases with recent imaging of the pelvis or in cases of planned open repair without extension into the pelvic vasculature, further imaging of the pelvis vasculature may not be needed. If venous phase or unenhanced CT has already been performed, additional imaging with CTA may not be required in some patients but may be needed for preprocedure sizing and evaluation of pathology.

CT Chest and Abdomen Without IV Contrast
There is no relevant literature CT chest and abdomen without contrast for the planning of thoracoabdominal aortic endovascular or open repair. Compared with CT of the chest, abdomen, and pelvis, exclusion of the pelvis from the field of view carries the drawback of precluding evaluation of the iliofemoral access vessels if endovascular repair is considered. If venous phase or unenhanced CT has already been performed, additional imaging with CTA may not be required in some patients but may be needed for preprocedure sizing and evaluation of pathology.

CTA Chest, Abdomen, and Pelvis With IV Contrast

The high spatial resolution and profound, homogenous enhancement of the aorta and branch vessels in CTA allows for excellent preoperative assessment. Prior studies dating back to the 2000s have shown CTA to be a valuable tool to evaluate anatomic suitability for endovascular repair of the thoracic or abdominal aorta [31,60-63]. With anatomic coverage from the aortic root to the superficial femoral arteries, CTA can rapidly evaluate the extent of thoracoabdominal aneurysm or dissection as well as provide information valuable for preoperative planning such as aortic tortuosity, branch vessel location and patency, and suitability of femoral access vessels for endovascular repair. CTA can also readily evaluate for complications related to aortic pathology that could affect surgical or procedural plan including aortic rupture, dissection extension, or malperfusion syndrome.

Although TAAA is traditionally treated with open repair, hybrid and endovascular repair of TAAA or dissections have increasingly been used over the past decade [14,64]. Techniques including snorkels/periscopes to allow perfusion of aortic branches, fenestrated EVAR, and branched EVAR have been used for thoracoabdominal aneurysms, and fenestration, branch vessel stenting, and true lumen stenting have progressively been used for thoracoabdominal dissection [9,14,64,65]. Many of these are complex procedures, and precise measurements of the aortic aneurysm or dissection before the procedure facilitates planning and ensures appropriate device availability at the time of procedure [9,65]. The thin slices, high spatial resolution, and isotropic data acquired with CTA permits advanced reconstruction techniques such as centerline measurements and double orthogonal measurements, permitting precise assessment of the aortic and branch vessel anatomy and detailed procedure planning [60-62,66,67].

Inclusion of the pelvis in the study also aids in procedure planning by allowing evaluation of the iliofemoral access vessels. Femoral access is typically preferred for endovascular repair, although access vessels must typically be suitable in size, tortuosity, and calcification of the iliac vessels to permit device delivery to the aorta. In patients with inappropriate iliofemoral vessels, groin cutdown with conduit, direct aortoiliac access, or brachial access can be used.

Before open or endovascular repair of a thoracoabdominal aneurysm or dissection, some authors have advocated for imaging for identification of the artery of Adamkiewicz, because preoperative identification could potentially reduce the risk of spinal cord ischemia [68,69]. Given the variability of the origin of this artery, preoperative identification of the origin of this vessel allows for operative planning that minimizes the risk of damage and can reduce surgical times [69]. Multiple studies evaluating the ability of CT and MRI to identify the artery of Adamkiewicz show that the artery can be identified and traced in >75% of patients, with some studies finding >90% identification [68,70-72].

CTA Chest and Abdomen With IV Contrast

Compared with CTA of the chest, abdomen, and pelvis, exclusion of the pelvis carries the drawback of precluding evaluation of the iliofemoral access vessels if endovascular repair is considered. Furthermore, if the thoracoabdominal dissection or aneurysm extends into the pelvis, a lack of pelvis evaluation could result in incomplete evaluation of the aortic pathology. In select cases with recent imaging of the pelvis or in cases of planned open repair without extension into the pelvic vasculature, further imaging of the pelvis vasculature may not be needed.

MRA Chest, Abdomen, and Pelvis Without and With IV Contrast

Although the spatial resolution of MRA without and with IV contrast is less than the spatial resolution of CTA with IV contrast, MRA provides good evaluation of the aorta and branch vessels to allow for procedural or operative planning [38,62,67]. A 2011 study compared image quality, vessel measurements, and proposed endograft selection among MRA and CTA in 30 patients scheduled for EVAR [67]. This analysis found small differences in measured aortic diameter at multiple locations, all <1 mm between MRA and CTA [67]. Ultimately, this study concluded that the image quality for both CTA and MRA was, in general, adequate and that differences were not clinically relevant because all 30 patients had the same endograft components selected based on measurements [67]. Although the study was focused on AAA, the result is likely applicable to measurements of thoracoabdominal aneurysm or dissection, with the caveat that the complexity of endovascular thoracoabdominal repair may place a higher value on precise measurements. MRA is thus able to evaluate the extent of thoracoabdominal aneurysm or dissection as well as to provide information valuable for preoperative planning such as aortic tortuosity, branch vessel location and patency, and suitability of femoral access vessels for endovascular repair. MRA can also evaluate for complications related to aortic pathology that could affect surgical or procedural plan including aortic rupture, dissection extension, or malperfusion syndrome.

Although TAAA is traditionally treated with open repair, hybrid and endovascular repair of TAAA or dissections have increasingly been used over the past decade [14,64]. Techniques including snorkels/periscopes to allow perfusion of aortic branches, fenestrated EVAR, and branched EVAR have been used for thoracoabdominal aneurysms, and fenestration, branch vessel stenting, and true lumen stenting have progressively been used for thoracoabdominal dissection [9,14,64,65]. Many of these are complex procedures, and precise measurements of the aortic aneurysm or dissection before procedure facilitates planning and ensures appropriate device availability at the time of procedure [9,65]

Inclusion of the pelvis in the study also aids in procedure planning by allowing evaluation of the iliofemoral access vessels. Femoral access is typically preferred for endovascular repair, although access vessels must typically be suitable in size, tortuosity, and calcification of the iliac vessels to permit device delivery to the aorta. In patients with inappropriate iliofemoral vessels, groin cutdown with conduit, direct aortoiliac access, or brachial access can be used.

Before open or endovascular repair of a thoracoabdominal aneurysm or dissection, some authors have advocated for imaging for identification of the artery of Adamkiewicz because preoperative identification could potentially reduce the risk of spinal cord ischemia [68]. Given the variability of the origin of this artery, preoperative identification of the origin of this vessel allows for operative planning that minimizes risk of damage. Multiple studies evaluating the ability of CT and MRI to identify the artery of Adamkiewicz show that the artery can be identified and traced in >75% of patients, with identification rates typically higher in MRA compared with CTA [68,70-73].

MRA Chest, Abdomen, and Pelvis Without IV Contrast

A 2012 study by Shaida et al [63] compared aortic measurements in 20 patients undergoing both CTA and noncontrast MRI before EVAR. The study measured vessel diameter at multiple points as well as several vessel lengths and found small discrepancies between MRI and CTA, typically <1 mm for diameters or 5 mm for lengths [63]. The authors concluded such measurements were unlikely to alter planning of the repair but favored CTA in most patients [63]. Although this study focused on AAA, the result is likely applicable to measurements of thoracoabdominal aneurysm or dissection, with the caveat that the complexity of endovascular thoracoabdominal repair may place a higher value on precise measurements. Similar conclusions were reached by a 2013 study comparing pre-EVAR MRI without IV contrast and CTA [61,74].

MRA Chest and Abdomen Without and With IV Contrast

Compared with MRA of the chest, abdomen, and pelvis, exclusion of the pelvis carries the drawback of precluding evaluation of the iliofemoral access vessels if endovascular repair is considered. Furthermore, if the thoracoabdominal dissection or aneurysm extends into the pelvis, a lack of pelvis evaluation could result in incomplete evaluation of the aortic pathology. In select cases with recent imaging of the pelvis or in cases of planned open repair without extension into the pelvic vasculature, further imaging of the pelvis vasculature may not be needed.

MRA Chest and Abdomen Without IV Contrast

Compared with MRA of the chest, abdomen, and pelvis, exclusion of the pelvis carries the drawback of precluding evaluation of the iliofemoral access vessels if endovascular repair is considered. Furthermore, if the thoracoabdominal dissection or aneurysm extends into the pelvis, a lack of pelvis evaluation could result in incomplete evaluation of the aortic pathology. In select cases with recent imaging of the pelvis or in cases of planned open repair without extension into the pelvic vasculature, further imaging of the pelvis vasculature may not be needed.

Radiography Chest

There is no relevant literature regarding the use of radiography for planning thoracoabdominal aortic endovascular or open repair.

Radiography Chest Abdomen Pelvis

There is no relevant literature regarding the use of radiography for planning thoracoabdominal aortic endovascular or open repair.

US Duplex Doppler Aorta Abdomen

There is no relevant literature regarding the use of duplex US for planning thoracoabdominal aortic endovascular or open repair. Although US can be used to evaluate the abdominal aorta for dissection or aneurysm, limitations to the evaluation of the spatial relationship of the aorta to branch vessels and the inability to visualize portions of the aorta limit its utility as a sole modality for procedural planning.

US Echocardiography Transthoracic Resting

There is no relevant literature regarding the use of TTE for planning thoracoabdominal aortic endovascular or open repair. Although TTE can evaluate for cardiac complications such as aortic valve regurgitation [33] and evaluate portions of the thoracic aorta, limitations to the evaluation of the spatial relationship of the aorta to branch vessels, the inability to visualize portions of the aorta, and a dependence on operator and patient characteristics limit its utility as a sole modality for procedural planning.

Variant 3: Follow-up after endovascular repair of thoracoabdominal aortic aneurysm or dissection.

Aortography Chest Abdomen Pelvis

Aortogram with DSA for evaluation of the thoracic and abdominal aorta has a sensitivity of up to 90% and a specificity of 95% for acute aortic syndrome [27]. The role of aortography for routine follow-up after endovascular repair is limited in favor of noninvasive modalities such as CTA and MRA, and CTA has been found to have a higher sensitivity than angiogram [75,76]. In cases of increasing aneurysm sac size likely to require treatment of endoleak, aortogram could be considered because it would allow rapid transition from diagnosis to treatment. Additional benefits of angiogram include the ability to evaluate directionality of endoleaks, which can be difficult on CTA [76].

CT Chest, Abdomen, and Pelvis With IV Contrast

There is no relevant literature regarding venous phase CT chest, abdomen, and pelvis for the follow-up of endovascular repair of thoracoabdominal aneurysm or dissection because most follow-up imaging uses an arterially timed contrast bolus in the form of a CTA (discussed below). However, contrast-enhanced CT can provide similar information as CTA in evaluating the size and extent of aortic pathology, although with a reduced sensitivity to delineating endoleak and subtle changes to aorta and branch artery diameter. Although typically not performed for the purpose of follow-up of thoracoabdominal aortic pathology, contrast-enhanced CT performed to evaluate for extravascular pathology can often assess for acute changes after endovascular repair including endoprosthesis migration or aortic rupture. If venous phase or unenhanced CT has already been performed, additional imaging with CTA may not be required in some patients.

CT Chest, Abdomen, and Pelvis Without and With IV Contrast

There is no relevant literature for venous and unenhanced CT chest, abdomen, and pelvis without an arterial phase for follow-up after thoracoabdominal endovascular repair. However, contrast-enhanced CT can provide similar information as CTA in evaluating the size and extent of aortic pathology, although with a reduced sensitivity to delineating endoleak and subtle changes to aorta and branch artery diameter. Although typically not performed for the purpose of follow-up of thoracoabdominal aortic pathology, contrast-enhanced CT performed to evaluate for extravascular pathology can often assess for acute changes after endovascular repair including endoprosthesis migration or aortic rupture. The addition of a noncontrast phase would be expected to aid in identifying endoleak and distinguishing endoleak from other sources of sac/false lumen opacification, although a lack of an arterial phase limits sensitivity. If venous phase or unenhanced CT has already been performed, additional imaging with CTA may not be required in some patients.

CT Chest, Abdomen, and Pelvis Without IV Contrast

Typical CT follow-up after endovascular thoracoabdominal aortic repair incorporates arterial and delayed venous phases to evaluate for endoleak [77]. However, unenhanced CT can be used to evaluate aortic caliber to detect changes to a thoracoabdominal aneurysm or aneurysmal degeneration of a thoracoabdominal dissection. Drawbacks of unenhanced imaging include an inability to identify endoleak, evaluate branch vessel patency, or evaluate for false lumen thrombosis in aortic dissection. Nonetheless, some authors have advocated for routine use of noncontrast-enhanced CT over contrast-enhanced CT in patients after EVAR with stable aneurysm sac size, with contrast-enhanced CTA used for evaluation if aortic sac size changes [32,76]. If venous phase or unenhanced CT has already been performed, additional imaging with CTA may not be required in some patients.

CT Chest and Abdomen With IV Contrast

There is no relevant literature regarding venous phase CT chest and abdomen for the follow-up of endovascular repair of thoracoabdominal aneurysm or dissection. Compared with CT of the chest, abdomen, and pelvis, evaluation of the chest and abdomen only without imaging of the pelvis may fail to detect changing or new pathology in the pelvic vasculature. If venous phase or unenhanced CT has already been performed, additional imaging with CTA may not be required in some patients.

CT Chest and Abdomen Without and With IV Contrast
There is no relevant literature for venous and unenhanced CT without an arterial phase for follow-up after thoracoabdominal endovascular repair.

Compared with CT of the chest, abdomen, and pelvis, evaluation of the chest and abdomen only without imaging of the pelvis may fail to detect changing or new pathology in the pelvic vasculature. If venous phase or unenhanced CT has already been performed, additional imaging with CTA may not be required in some patients.

CT Chest and Abdomen Without IV Contrast
Compared with CT of the chest, abdomen, and pelvis, evaluation of the chest and abdomen only without imaging of the pelvis may fail to detect changing or new pathology in the pelvic vasculature. If venous phase or unenhanced CT has already been performed, additional imaging with CTA may not be required in some patients.

CTA Chest, Abdomen, and Pelvis With IV Contrast
CTA is ideal for evaluation after endovascular repair because of its sensitivity in detecting endoleaks, ability to detect changes in aortic diameter, evaluation of false lumen thrombosis, endograft infection, and assessment of branch vessel/stent patency [1,2,77-79]. Because most endovascular repairs of TAAA or dissection are complex, the need for routine surveillance after treatment is crucial, and often, lifelong follow-up is recommended. A 2016 study of 354 patients undergoing endovascular repair for thoracoabdominal aortic pathology underscores the need for close follow-up, because 36% of patients required further intervention within 36 months, most commonly for endoleak [14]. Typically, follow-up imaging is obtained at 1, 3, and 6 months after intervention to evaluate for endoleak, increase in aortic diameter, incomplete false lumen thrombosis (in dissection), and other procedure complications, and prior studies have shown poor compliance with follow-up and increased risk of aortic rupture in these patients with limited imaging follow-up [17,80]. After 6 months, individualized imaging follow-up may be planned based on personal risk factors, with imaging typically at 6- to 12-month intervals.

Protocols for CTA follow-up after endovascular thoracoabdominal repair vary between institutions, but typical protocols include an unenhanced, arterial, and delayed phase (60–300 seconds after contrast injection) imaging [77]. The unenhanced phase provides utility in differentiating intraluminal opacities such as procedural material from endoleak on contrast-enhanced phases. Use of a dual-energy acquired delayed venous phase to create a virtual noncontrast phase has also been shown to be effective in identifying endoleaks while eliminating the need for an additional noncontrast phase [77,81].

Although direct evidence comparing CTA to other modalities in endoleak identification after endovascular thoracoabdominal aneurysm repair is lacking, multiple studies and meta-analyses have compared CTA with MRI and US for endoleak identification after EVAR for AAA [78,79,82,83]. A meta-analysis by Guo et al [82] in 2016 evaluated 3,853 patients after EVAR with paired scans of different modalities (CTA, MRA, US) within a 1-month period. In 2,346 paired CTA and duplex US scans, CTA identified 214 additional endoleaks not seen on duplex US (including 26 type I or type III endoleaks), whereas duplex US identified 77 additional endoleaks not seen on CTA (no type I or III endoleaks) [82]. In 1,694 paired CTA and MRA scans, CTA identified 2 additional endoleaks, whereas MRA identified 42 additional endoleaks [82]. A subsequent meta-analysis in 2018 by Zaiem et al [84] also noted that MRI identified more endoleaks than CTA. These findings suggest higher sensitivity of MRI to detect endoleaks, although the authors caution that the increased endoleaks identified could represent false-positive findings or endoleaks that are not clinically important [84].

CTA Chest and Abdomen With IV Contrast
Compared with CTA of the chest, abdomen, and pelvis, evaluation of the chest and abdomen only without imaging of the pelvis may fail to detect changing or new pathology in the pelvic vasculature that could require additional intervention.

MRA Chest, Abdomen, and Pelvis Without and With IV Contrast
The spatial resolution of MRA is less than that of CTA, but the ability to detect branch vessel complications, endoleaks, stent graft complication, or infection has established MRA as an effective modality for imaging after endovascular repair, particularly for nitinol stent grafts, which have reduced susceptibility artifact. Because most thoracoabdominal aortic repairs are complex, the need for routine surveillance after treatment is crucial, and often, lifelong follow-up is recommended. A 2016 study of 354 patients undergoing endovascular repair for

thoracoabdominal aortic pathology underscores the need for close follow-up, because 36% of patients required further intervention within 36 months, most commonly for endoleak [14]. Typically, follow-up imaging is obtained at 1, 3, and 6 months after intervention to evaluate for endoleak, increase in aortic diameter, incomplete false lumen thrombosis (in dissection), and other procedure complications, and prior studies have shown poor compliance with follow-up with increased risk of aortic rupture in patients with poor follow-up [17,80]. After 6 months, individualized imaging follow-up may be planned based on personal risk factors, with imaging typically at 6 to 12 month intervals.

Early studies evaluating the ability of MRA to evaluate for endoleak or other complication after EVAR established MRI as a suitable alternative to CTA [78,85,86]. Direct evidence comparing MRA with IV contrast to other modalities in endoleak identification after endovascular thoracoabdominal aneurysm repair is lacking, but multiple additional studies and meta-analyses have compared MRA with CTA in identifying endoleaks after EVAR [78,79,82,83,85,86]. A meta-analysis by Guo et al [82] in 2016 evaluated 3,853 patients after EVAR with paired scans of different modalities (CTA, MRA, US) obtained within a 1-month period. In 1,694 paired CTA and MRA scans, CTA identified 2 additional endoleaks, whereas MRA identified 42 additional endoleaks [82]. A subsequent meta-analysis in 2018 by Zaiem et al also noted that MRI identified more endoleaks than CTA [84]. These findings suggest a higher sensitivity of MRI in identification of endoleak compared with CTA, although the authors caution that the increased endoleaks identified could represent false-positive findings or endoleaks that are not clinically important [84].

MRA with IV contrast also allows superior evaluation of flow dynamics compared with CTA. Time resolved and 4-D flow MRA can be used to improve detection and classification of endoleaks [76,87,88]. Use of multiple phases of contrast can be used in 4-D flow MRA to ascertain not only the presence of endoleak but also the endoleak type [88]. MRA with IV contrast has also shown value in predicting the persistence of type II endoleak. A retrospective review of MRAs with type II endoleak performed by Katahashi et al determined that the use of flow quantification could be used to accurately predict persistence or resolution of type II endoleak after EVAR, although this algorithm has not been applied prospectively [20].

MRA Chest, Abdomen, and Pelvis Without IV Contrast

Literature supporting the use of MRA without IV contrast for evaluation after endovascular thoracoabdominal aortic repair is limited compared with evidence of MRA with IV contrast. A 2019 study evaluating 8 patients used a noncontrast MRI protocol to assess for endoleak after EVAR [89]. This study compared noncontrast MRA with contrast-enhanced CTA and angiogram and found the MRAs had comparable ability to detect endoleaks and assess aneurysm size [89]. The applicability of these findings to imaging post-thoracoabdominal endovascular intervention is unknown, although applicability may be incomplete because of multiple stents within the aorta and branch vessels. Additionally, the ability of this sequence to obtain widespread use is unclear. As such, noncontrast MRA would generally be expected to have a lower sensitivity for endoleak, false lumen thrombosis, or branch vessel patency, although evidence is lacking.

MRA Chest and Abdomen Without and With IV Contrast

Compared with MRA of the chest, abdomen, and pelvis, evaluation of the chest and abdomen only without imaging of the pelvis carries the advantage of reduced imaging time although may fail to detect changing or new pathology in the pelvic vasculature that could require further intervention.

MRA Chest and Abdomen Without IV Contrast

Compared with MRA of the chest, abdomen, and pelvis, evaluation of the chest and abdomen only without imaging of the pelvis carries the advantage of reduced imaging time although may fail to detect changing or new pathology in the pelvic vasculature that could require further intervention.

Radiography Chest

Postintervention radiography can be used to monitor endograft position and integrity, with location relative to bony landmarks used to infer possible stent migration [76]. Additionally, prior studies have reported the value of radiography to evaluate for endograft fracture and kinking [76,90]. However, the low incidence of stent fracture and the inability of radiography to evaluate for increasing aneurysm sac size, branch occlusion, and many other complications limits value in routine use. Additionally, a radiograph of the chest only is likely to include only a portion of the repaired aorta within the field of view.

Radiography Chest Abdomen Pelvis
Postintervention radiography can be used to monitor endograft position and integrity, with location relative to bony landmarks used to infer possible stent migration [76]. Additionally, prior studies have reported the value of radiography to evaluate for endograft fracture and kinking [76,90]. However, the low incidence of stent fracture and the inability of radiography to evaluate for increasing aneurysm sac size, branch occlusion, and many other complications limits value in routine use.

US Duplex Doppler Aorta Abdomen
Duplex US of the abdominal aorta carries the advantages of being a readily obtainable bedside examination for evaluation of the distal thoracic and abdominal aorta. After EVAR, duplex US can be used to evaluate aortic diameter and presence of endoleak, with a good correlation of aortic size with CTA in most patients [76,91].

Meta-analyses by Guo et al in 2016 [82] and Baliyan et al in 2018 [92] compared CTA with duplex US and found improved sensitivity for endoleak detection with CTA over US. However, this study along with multiple other studies suggests that contrast-enhanced duplex US may be comparable to improved ability to detect endoleaks compared with CTA [82,84,92]. Although the sensitivity of duplex US for endoleak is low relative to CTA, the ability to evaluate directionality of flow is a potential advantage. Presence of bidirectional "to-and-fro" flow and low peak systolic velocity of flow within an excluded aneurysm sac are associated with spontaneous endoleak resolution, so duplex US may help to identify endoleaks that are more likely to persist [76,93].

US Echocardiography Transthoracic Resting
TTE allows visualization of the heart and portions of the thoracic aorta. However, portions of the proximal descending thoracic aorta may be poorly visualized with TTE, and examination may be limited by poor acoustic windows, creating the possibility of false-negative examinations in following patients after endovascular thoracoabdominal aortic repair [58]. These characteristics have resulted in a low sensitivity of 31% to 55% for diagnosis of acute type B aortic dissection on TTE [33]. TTE is also limited by the ability to visualize the abdominal aorta to determine the extent of thoracoabdominal aortic pathology.

Variant 4: Follow-up after open repair of thoracoabdominal aortic aneurysm or dissection.

Aortography Chest Abdomen Pelvis
There is no relevant literature regarding the use of aortography in the evaluation of follow-up of open repair of TAAA or dissection. Aortogram with DSA for evaluation of the thoracic and abdominal aorta has a sensitivity of up to 90% and a specificity of 95% for acute aortic syndrome [27]. Although it has the advantage of allowing immediate intervention if an abnormality is identified, aortography is an invasive procedure that is now typically performed for treatment after diagnosis of a new or worsening aortic pathology.

CT Chest, Abdomen, and Pelvis With IV Contrast
There is no relevant literature regarding venous phase CT chest, abdomen, and pelvis for the follow-up of open repair of TAAA or dissection because most follow-up imaging uses an arterially timed contrast bolus in the form of a CTA (discussed below). However, contrast-enhanced CT can provide similar information as CTA in evaluating the size and extent of aortic pathology and in identifying postsurgical complications. If venous phase or unenhanced CT has already been performed, additional imaging with CTA may not be required in some patients.

CT Chest, Abdomen, and Pelvis Without and With IV Contrast
There is no relevant literature regarding venous phase CT chest, abdomen, and pelvis with noncontrast phase for the follow-up of open repair of TAAA or dissection because most follow-up imaging uses an arterially timed contrast bolus in the form of a CTA (discussed below). However, contrast-enhanced CT can provide similar information as CTA in evaluating the size and extent of aortic pathology and in identifying postsurgical complications. If venous phase or unenhanced CT has already been performed, additional imaging with CTA may not be required in some patients.

CT Chest, Abdomen, and Pelvis Without IV Contrast
There is no relevant literature for CT chest, abdomen, and pelvis without IV contrast in the evaluation of follow-up of open repair of TAAA or dissection. Although most follow-up after open thoracoabdominal aortic repair is performed with IV contrast [29-31], select groups of patients may be monitored with noncontrast CT to evaluate measurements of aortic size and for surrounding changes that could suggest inflammation or infection. If venous phase or unenhanced CT has already been performed, additional imaging with CTA may not be required in some patients.

CT Chest and Abdomen With IV Contrast
There is no relevant literature regarding venous phase CT chest and abdomen for the follow-up of open repair of TAAA or dissection. Compared with CT of the chest, abdomen, and pelvis, exclusion of the pelvis may fail to detect changing or new pathology in the pelvic vasculature. If venous phase or unenhanced CT has already been performed, additional imaging with CTA may not be required in some patients.

CT Chest and Abdomen Without and With IV Contrast
There is no relevant literature regarding venous phase CT chest, abdomen, and pelvis with noncontrast phase for the follow-up of open repair of TAAA or dissection. Compared with CT of the chest, abdomen, and pelvis, evaluation of the chest and abdomen only without imaging of the pelvis may fail to detect changing or new pathology in the pelvic vasculature. If venous phase or unenhanced CT has already been performed, additional imaging with CTA may not be required in some patients.

CT Chest and Abdomen Without IV Contrast
There is no relevant literature for CT chest and abdomen without IV contrast in the evaluation of follow-up of open repair of TAAA or dissection. Compared with CT of the chest, abdomen, and pelvis, exclusion of the pelvis may fail to detect changing or new pathology in the pelvic vasculature. If venous phase or unenhanced CT has already been performed, additional imaging with CTA may not be required in some patients.

CTA Chest, Abdomen, and Pelvis With IV Contrast
CTA of the chest, abdomen, and pelvis with IV contrast uses fast scan times to allow for rapid evaluation of the aorta. Acquisition of thin axial slices with subsequent reconstruction along with extensive and homogenous luminal opacification allows for precise and reproducible measurements of the aorta, which are valuable for monitoring aortic growth and interval changes [33,34].

In addition to monitoring aortic size and postsurgical complications such as anastomotic pseudoaneurysm, CTA can evaluate for endograft complications, kinking or occlusion/stenosis of branches of the graft, infection, or complications including thoracoabdominal aneurysm rupture or dissection extension [31,35].

Evidence comparing CTA with MRA for follow-up after surgical thoracoabdominal aortic repair is limited. A 2015 review of imaging of the thoracic aorta concluded that contrast-enhanced CT was the optimal modality evaluation of the aorta after surgical repair, although MRI is also comparable and with image resolution comparable to CTA [33].

Compared with CTA of the chest and abdomen, imaging of the pelvis carries the benefit of evaluation of the iliofemoral vessels to assess for new or worsening pathology of the pelvic vessels.

CTA Chest and Abdomen With IV Contrast
Compared with CTA of the chest, abdomen, and pelvis, CTA of the chest and abdomen may fail to identify new or worsening pelvic pathology.

MRA Chest, Abdomen, and Pelvis Without and With IV Contrast
MRA of the chest, abdomen, and pelvis without and with IV contrast can be used as an alternative to CTA for follow-up after open thoracoabdominal aortic repair. Spatial resolution of MRA is not as high as CTA, although some authors have found MRI to be an alternative option for imaging in younger patients [33].

In addition to monitoring aortic size and postsurgical complication such as anastomotic pseudoaneurysm, CTA can evaluate for graft complications, kinking or occlusion/stenosis of branches of the graft, infection, or complications including thoracoabdominal aneurysm rupture or dissection extension. MRA can also assess flow dynamics including wall stress and turbulent flow patterns, which may be valuable in certain patients [23,24].

Compared with MRA of the chest and abdomen, imaging of the pelvis carries the benefit of evaluation of the iliofemoral vessels to assess for new or worsening pathology of the pelvic vessels. The drawback of inclusion of the pelvis is increased acquisition time.

MRA Chest, Abdomen, and Pelvis Without IV Contrast
Evidence supporting use of MRA without IV contrast for evaluation after open thoracoabdominal aortic repair is limited compared with evidence of MRA with IV contrast.

Similar to CTA, MRA of the thoracoabdominal aorta allows for precise and reproducible assessment of aortic sac size in aneurysm or extent of dissection in thoracoabdominal aortic dissection [33,37-39]. Multiple unenhanced

MRA techniques such as time-of-flight, phase-contrast imaging, and SSFP have been developed that allow for evaluation of aortic dissection and aneurysm, including after open surgical repair [44,45]. Even without IV contrast, MRA can be used to precisely evaluate the thoracoabdominal aorta [37,39]. A 2017 observational study comparing AAA measurements in contrast-enhanced CTA and noncontrast-enhanced MRA showed strong agreement, with intraclass coefficient >0.99 and interobserver reproducibility >0.99 for both CTA and MRA [45].

Although some studies have shown more accurate measurements with contrast-enhanced MRA compared with noncontrast-enhanced MRA, other studies have shown equal ability to detect aortic pathology and to measure aortic size [44,50,51]. A 2014 study comparing thoracic aortic measurements and pathology in 76 patients undergoing both contrast- and noncontrast-enhanced MRA showed high agreement between study types, with low intra- and interobserver dependency (intraclass correlation coefficient 0.99) [51]. A similar 2017 study comparing thoracic aorta measurements/findings on contrast- and noncontrast-enhanced MRA performed on a group of 50 patients favored noncontrast-enhanced MRA over contrast-enhanced MRA as the technique of choice because of superior image quality and better vessel sharpness in the ascending aorta [44]. Although these studies do not focus on postsurgical patients, the findings are likely applicable to this patient population.

MRA Chest and Abdomen Without and With IV Contrast
Compared with MRA of the chest, abdomen, and pelvis, imaging of the chest and abdomen reduces acquisition time, although is unable to assess for new or worsening pathology within the pelvis.

MRA Chest and Abdomen Without IV Contrast
Compared with MRA of the chest, abdomen, and pelvis, imaging of the chest and abdomen reduces acquisition time, although is unable to assess for new or worsening pathology within the pelvis.

Radiography Chest
There is no relevant literature for radiography in the evaluation of follow-up of open repair of TAAA or dissection. After surgical repair of the thoracoabdominal aorta, radiography is unlikely to carry a sufficient sensitivity or specificity to be used routinely.

Radiography Chest Abdomen Pelvis
There is no relevant literature for radiography in the evaluation of follow-up of open repair of TAAA or dissection. After surgical repair of the thoracoabdominal aorta, radiography is unlikely to carry a sufficient sensitivity or specificity to be used routinely.

US Duplex Doppler Aorta Abdomen
Duplex US of the abdominal aorta is an option for evaluation of the thoracoabdominal aorta, although the ability to evaluate the aorta above the diaphragm may be markedly limited by acoustic windows. Prior studies comparing US, CT, and MRI of the abdominal aorta found that US is a reliable method to diagnose and follow AAAs [56]. In the evaluation of thoracoabdominal aortic dissection, US can also be used to evaluate blood flow in the true and false lumens and to directly and dynamically monitor the motion of dissection flaps [43]. As such, abdomen US can be performed serially to evaluate for aortic size changes or dissection hemodynamic changes. However, a limited ability to evaluate the thoracic aorta with dependence on patient acoustic windows could result in poor image quality or the inability to view changes to the aorta.

US Echocardiography Transthoracic Resting
There is no relevant literature regarding the use of TTE in the evaluation of the thoracoabdominal aorta after open repair. TTE allows visualization of the heart and portions of the thoracic aorta. However, portions of the proximal descending thoracic aorta may be poorly visualized with TTE, and examination may be limited by poor acoustic windows, creating the possibility of false-negative examinations in following patients after thoracoabdominal aortic repair [58]. TTE has limited by ability to visualize the abdominal aorta to determine the extent of thoracoabdominal aortic pathology and may therefore be limited to patients with thoracoabdominal surgical repair involving only the thoracic and proximal abdominal aorta.

Summary of Recommendations

- **Variant 1**: MRA chest abdomen pelvis without and with IV contrast, MRA chest abdomen pelvis without IV contrast, or CTA chest abdomen pelvis with IV contrast is usually appropriate for a patient without or with new symptoms undergoing follow-up of a known TAAA or dissection without repair. Contrast-enhanced imaging is generally preferred but may not be necessary in all patients. These procedures are equivalent alternatives (ie, only one procedure will be ordered to provide the clinical information to effectively manage the patient's care).

- **Variant 2**: MRA chest abdomen pelvis without and with IV contrast, MRA chest abdomen pelvis without IV contrast, or CTA chest abdomen pelvis with IV contrast is usually appropriate for a patient undergoing planning for endovascular or open repair of a thoracoabdominal aorta aneurysm or dissection. These procedures are equivalent alternatives (ie, only one procedure will be ordered to provide the clinical information to effectively manage the patient's care). The panel did not agree on recommending MRA chest and abdomen without and with IV contrast, CT chest abdomen pelvis with IV contrast, CT chest abdomen pelvis without and with IV contrast, or CTA chest and abdomen with IV contrast for this clinical scenario. There is insufficient medical literature to conclude whether or not these patients would benefit from these procedures in this clinical scenario. Imaging in this patient population is controversial but may be appropriate.
- **Variant 3**: MRA chest abdomen pelvis without and with IV contrast or CTA chest abdomen pelvis with IV contrast is usually appropriate for a patient undergoing follow-up after endovascular repair of a TAAA or dissection. These procedures are equivalent alternatives (ie, only one procedure will be ordered to provide the clinical information to effectively manage the patient's care). The panel did not agree on recommending aortography chest abdomen pelvis, MRA chest and abdomen without and with IV contrast, or CTA chest and abdomen with IV contrast for this clinical scenario. There is insufficient medical literature to conclude whether or not these patients would benefit from these procedures in this clinical scenario. Imaging in this patient population is controversial but may be appropriate.
- **Variant 4**: MRA chest abdomen pelvis without and with IV contrast or CTA chest abdomen pelvis with IV contrast is usually appropriate for a patient undergoing follow-up after open repair of a TAAA or dissection. These procedures are equivalent alternatives (ie, only one procedure will be ordered to provide the clinical information to effectively manage the patient's care).

Supporting Documents

The evidence table, literature search, and appendix for this topic are available at https://acsearch.acr.org/list. The appendix includes the strength of evidence assessment and the final rating round tabulations for each recommendation.

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

Appropriateness Category Names and Definitions

Appropriateness Category Name	Appropriateness Rating	Appropriateness Category Definition
Usually Appropriate	7, 8, or 9	The imaging procedure or treatment is indicated in the specified clinical scenarios at a favorable risk-benefit ratio for patients.
May Be Appropriate	4, 5, or 6	The imaging procedure or treatment may be indicated in the specified clinical scenarios as an alternative to imaging procedures or treatments with a more favorable risk-benefit ratio, or the risk-benefit ratio for patients is equivocal.
May Be Appropriate (Disagreement)	5	The individual ratings are too dispersed from the panel median. The different label provides transparency regarding the panel's recommendation. "May be appropriate" is the rating category and a rating of 5 is assigned.
Usually Not Appropriate	1, 2, or 3	The imaging procedure or treatment is unlikely to be indicated in the specified clinical scenarios, or the risk-benefit ratio for patients is likely to be unfavorable.

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, because of both 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 with 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 [94].

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."

References

1. Bonci G, Steigner ML, Hanley M, et al. ACR Appropriateness Criteria® Thoracic Aorta Interventional Planning and Follow-Up. J Am Coll Radiol 2017;14:S570-S83.
2. Francois CJ, Skulborstad EP, Majdalany BS, et al. ACR Appropriateness Criteria® Abdominal Aortic Aneurysm: Interventional Planning and Follow-Up. J Am Coll Radiol 2018;15:S2-S12.
3. Coselli JS, LeMaire SA, Preventza O, et al. Outcomes of 3309 thoracoabdominal aortic aneurysm repairs. J Thorac Cardiovasc Surg 2016;151:1323-37.
4. Kang PC, Bartek MA, Shalhub S, Nathan DP, Sweet MP. Survival and patient-centered outcome in a disease-based observational cohort study of patients with thoracoabdominal aortic aneurysm. J Vasc Surg 2019;70:1427-35.
5. Ockert S, Riemensperger M, von Tengg-Kobligk H, Schumacher H, Eckstein HH, Bockler D. Complex abdominal aortic pathologies: operative and midterm results after pararenal aortic aneurysm and type IV thoracoabdominal aneurysm repair. Vascular 2009;17:121-8.
6. Bianchini Massoni C, Geisbusch P, Gallitto E, Hakimi M, Gargiulo M, Bockler D. Follow-up outcomes of hybrid procedures for thoracoabdominal aortic pathologies with special focus on graft patency and late mortality. J Vasc Surg 2014;59:1265-73.
7. Hughes GC, Barfield ME, Shah AA, et al. Staged total abdominal debranching and thoracic endovascular aortic repair for thoracoabdominal aneurysm. J Vasc Surg 2012;56:621-9.
8. Markatis F, Petrosyan A, Abdulamit T, Bergeron P. Hybrid repair with antegrade visceral artery debranching: the preferred treatment option for thoracoabdominal aneurysms in high-risk patients. J Endovasc Ther 2012;19:356-62.
9. Lobato AC, Camacho-Lobato L. A new technique to enhance endovascular thoracoabdominal aortic aneurysm therapy--the sandwich procedure. Semin Vasc Surg 2012;25:153-60.
10. Oderich GS, Ribeiro M, Reis de Souza L, Hofer J, Wigham J, Cha S. Endovascular repair of thoracoabdominal aortic aneurysms using fenestrated and branched endografts. J Thorac Cardiovasc Surg 2017;153:S32-S41 e7.
11. Schwierz E, Kolvenbach RR, Yoshida R, Yoshida W, Alpaslan A, Karmeli R. Experience with the sandwich technique in endovascular thoracoabdominal aortic aneurysm repair. J Vasc Surg 2014;59:1562-9.

12. Sweet MP, Starnes BW, Tatum B. Endovascular treatment of thoracoabdominal aortic aneurysm using physician-modified endografts. J Vasc Surg 2015;62:1160-7.
13. Clough RE, Martin-Gonzalez T, Van Calster K, et al. Endovascular Repair of Thoracoabdominal and Arch Aneurysms in Patients with Connective Tissue Disease Using Branched and Fenestrated Devices. Ann Vasc Surg 2017;44:158-63.
14. Eagleton MJ, Follansbee M, Wolski K, Mastracci T, Kuramochi Y. Fenestrated and branched endovascular aneurysm repair outcomes for type II and III thoracoabdominal aortic aneurysms. J Vasc Surg 2016;63:930-42.
15. Haulon S, D'Elia P, O'Brien N, et al. Endovascular repair of thoracoabdominal aortic aneurysms. Eur J Vasc Endovasc Surg 2010;39:171-8.
16. Law Y, Kolbel T, Rohlffs F, et al. Safety and durability of infrarenal aorta as distal landing zone in fenestrated or branched endograft repair for thoracoabdominal aneurysm. J Vasc Surg 2019;69:334-40.
17. Mell MW, Baker LC, Dalman RL, Hlatky MA. Gaps in preoperative surveillance and rupture of abdominal aortic aneurysms among Medicare beneficiaries. J Vasc Surg 2014;59:583-8.
18. Collard M, Sutphin PD, Kalva SP, et al. ACR Appropriateness Criteria® Abdominal Aortic Aneurysm Follow-up (Without Repair). J Am Coll Radiol 2019;16:S2-S6.
19. Jamalidinan F, Hassanabad AF, Francois CJ, Garcia J. Four-dimensional-flow Magnetic Resonance Imaging of the Aortic Valve and Thoracic Aorta. Radiol Clin North Am 2020;58:753-63.
20. Katahashi K, Sano M, Takehara Y, et al. Flow dynamics of type II endoleaks can determine sac expansion after endovascular aneurysm repair using four-dimensional flow-sensitive magnetic resonance imaging analysis. J Vasc Surg 2019;70:107-16 e1.
21. Kolipaka A, Illapani VS, Kenyhercz W, et al. Quantification of abdominal aortic aneurysm stiffness using magnetic resonance elastography and its comparison to aneurysm diameter. J Vasc Surg 2016;64:966-74.
22. Midulla M, Moreno R, Baali A, et al. Haemodynamic imaging of thoracic stent-grafts by computational fluid dynamics (CFD): presentation of a patient-specific method combining magnetic resonance imaging and numerical simulations. Eur Radiol 2012;22:2094-102.
23. Sieren MM, Schultz V, Fujita B, et al. 4D flow CMR analysis comparing patients with anatomically shaped aortic sinus prostheses, tube prostheses and healthy subjects introducing the wall shear stress gradient: a case control study. J Cardiovasc Magn Reson 2020;22:59.
24. Suh GY, Les AS, Tenforde AS, et al. Quantification of particle residence time in abdominal aortic aneurysms using magnetic resonance imaging and computational fluid dynamics. Ann Biomed Eng 2011;39:864-83.
25. Ichihashi S, Marugami N, Tanaka T, et al. Preliminary experience with superparamagnetic iron oxide-enhanced dynamic magnetic resonance imaging and comparison with contrast-enhanced computed tomography in endoleak detection after endovascular aneurysm repair. J Vasc Surg 2013;58:66-72.
26. Sadat U, Taviani V, Patterson AJ, et al. Ultrasmall superparamagnetic iron oxide-enhanced magnetic resonance imaging of abdominal aortic aneurysms--a feasibility study. Eur J Vasc Endovasc Surg 2011;41:167-74.
27. Lichtenberger JP, 3rd, Franco DF, Kim JS, Carter BW. MR Imaging of Thoracic Aortic Disease. Top Magn Reson Imaging 2018;27:95-102.
28. Engellau L, Albrechtsson U, Dahlstrom N, Norgren L, Persson A, Larsson EM. Measurements before endovascular repair of abdominal aortic aneurysms. MR imaging with MRA vs. angiography and CT. Acta Radiol 2003;44:177-84.
29. Bolen MA, Popovic ZB, Tandon N, Flamm SD, Schoenhagen P, Halliburton SS. Image quality, contrast enhancement, and radiation dose of ECG-triggered high-pitch CT versus non-ECG-triggered standard-pitch CT of the thoracoabdominal aorta. AJR Am J Roentgenol 2012;198:931-8.
30. Hinzpeter R, Eberhard M, Gutjahr R, et al. CT Angiography of the Aorta: Contrast Timing by Using a Fixed versus a Patient-specific Trigger Delay. Radiology 2019;291:531-38.
31. Yang S, Li X, Chao B, et al. Abdominal aortic intimal flap motion characterization in acute aortic dissection: assessed with retrospective ECG-gated thoracoabdominal aorta dual-source CT angiography. PLoS One 2014;9:e87664.
32. Bobadilla JL, Suwanabol PA, Reeder SB, Pozniak MA, Bley TA, Tefera G. Clinical implications of non-contrast-enhanced computed tomography for follow-up after endovascular abdominal aortic aneurysm repair. Ann Vasc Surg 2013;27:1042-8.
33. Goldstein SA, Evangelista A, Abbara S, et al. Multimodality imaging of diseases of the thoracic aorta in adults: from the American Society of Echocardiography and the European Association of Cardiovascular Imaging: endorsed by the Society of Cardiovascular Computed Tomography and Society for Cardiovascular Magnetic Resonance. J Am Soc Echocardiogr 2015;28:119-82.

34. Lu TL, Rizzo E, Marques-Vidal PM, Segesser LK, Dehmeshki J, Qanadli SD. Variability of ascending aorta diameter measurements as assessed with electrocardiography-gated multidetector computerized tomography and computer assisted diagnosis software. Interact Cardiovasc Thorac Surg 2010;10:217-21.
35. Willemink MJ, Meijs MF, Cramer MJ, et al. Coronary artery assessment on electrocardiogram-gated thoracoabdominal multidetector computed tomographic angiography for aortic evaluation. J Comput Assist Tomogr 2014;38:185-9.
36. Natsume K, Shiiya N, Takehara Y, et al. Characterizing saccular aortic arch aneurysms from the geometry-flow dynamics relationship. J Thorac Cardiovasc Surg 2017;153:1413-20 e1.
37. Bireley WR, 2nd, Diniz LO, Groves EM, Dill K, Carroll TJ, Carr JC. Orthogonal measurement of thoracic aorta luminal diameter using ECG-gated high-resolution contrast-enhanced MR angiography. J Magn Reson Imaging 2007;26:1480-5.
38. Clough RE, Waltham M, Giese D, Taylor PR, Schaeffter T. A new imaging method for assessment of aortic dissection using four-dimensional phase contrast magnetic resonance imaging. J Vasc Surg 2012;55:914-23.
39. Krishnam MS, Tomasian A, Malik S, Desphande V, Laub G, Ruehm SG. Image quality and diagnostic accuracy of unenhanced SSFP MR angiography compared with conventional contrast-enhanced MR angiography for the assessment of thoracic aortic diseases. Eur Radiol 2010;20:1311-20.
40. Strayer RJ. Thoracic Aortic Syndromes. Emerg Med Clin North Am 2017;35:713-25.
41. Laissy JP, Blanc F, Soyer P, et al. Thoracic aortic dissection: diagnosis with transesophageal echocardiography versus MR imaging. Radiology 1995;194:331-6.
42. Zhou C, Qiao H, He L, et al. Characterization of atherosclerotic disease in thoracic aorta: A 3D, multicontrast vessel wall imaging study. Eur J Radiol 2016;85:2030-35.
43. Liu F, Huang L. Usefulness of ultrasound in the management of aortic dissection. Rev Cardiovasc Med 2018;19:103-09.
44. van Kesteren F, Elattar MA, van Lienden KP, Baan J, Jr., Marquering HA, Planken RN. Non-contrast enhanced navigator-gated balanced steady state free precession magnetic resonance angiography as a preferred magnetic resonance technique for assessment of the thoracic aorta. Clin Radiol 2017;72:695 e1-95 e6.
45. Zhu C, Tian B, Leach JR, et al. Non-contrast 3D black blood MRI for abdominal aortic aneurysm surveillance: comparison with CT angiography. Eur Radiol 2017;27:1787-94.
46. Lim RP, Singh SG, Hornsey E, et al. Highly Accelerated Breath-Hold Noncontrast Electrocardiographically- and Pulse-Gated Balanced Steady-State Free Precession Magnetic Resonance Angiography of the Thoracic Aorta: Comparison With Electrocardiographically-Gated Computed Tomographic Angiography. J Comput Assist Tomogr 2019;43:323-32.
47. Zhu C, Haraldsson H, Kallianos K, et al. Gated thoracic magnetic resonance angiography at 3T: noncontrast versus blood pool contrast. Int J Cardiovasc Imaging 2018;34:475-83.
48. Sohns JM, Staab W, Menke J, et al. Vascular and extravascular findings on magnetic resonance angiography of the thoracic aorta and the origin of the great vessels. J Magn Reson Imaging 2014;40:988-95.
49. Kramer U, Fenchel M, Laub G, et al. Low-dose, time-resolved, contrast-enhanced 3D MR angiography in the assessment of the abdominal aorta and its major branches at 3 Tesla. Acad Radiol 2010;17:564-76.
50. Srichai MB, Kim S, Axel L, Babb J, Hecht EM. Non-gadolinium-enhanced 3-dimensional magnetic resonance angiography for the evaluation of thoracic aortic disease: a preliminary experience. Tex Heart Inst J 2010;37:58-65.
51. von Knobelsdorff-Brenkenhoff F, Gruettner H, Trauzeddel RF, Greiser A, Schulz-Menger J. Comparison of native high-resolution 3D and contrast-enhanced MR angiography for assessing the thoracic aorta. Eur Heart J Cardiovasc Imaging 2014;15:651-8.
52. Zhu C, Leach JR, Tian B, et al. Evaluation of the distribution and progression of intraluminal thrombus in abdominal aortic aneurysms using high-resolution MRI. J Magn Reson Imaging 2019;50:994-1001.
53. Lai V, Tsang WK, Chan WC, Yeung TW. Diagnostic accuracy of mediastinal width measurement on posteroanterior and anteroposterior chest radiographs in the depiction of acute nontraumatic thoracic aortic dissection. Emerg Radiol 2012;19:309-15.
54. Mongeon FP, Marcotte F, Terrone DG. Multimodality Noninvasive Imaging of Thoracic Aortic Aneurysms: Time to Standardize? Can J Cardiol 2016;32:48-59.
55. von Kodolitsch Y, Nienaber CA, Dieckmann C, et al. Chest radiography for the diagnosis of acute aortic syndrome. Am J Med 2004;116:73-7.

56. das Chagas de Azevedo F, Zerati AE, Blasbalg R, Wolosker N, Puech-Leao P. Comparison of ultrasonography, computed tomography, and magnetic resonance imaging with intraoperative measurements in the evaluation of abdominal aortic aneurysms. Clinics (Sao Paulo) 2005;60:21-8.
57. Evangelista A, Flachskampf FA, Erbel R, et al. Echocardiography in aortic diseases: EAE recommendations for clinical practice. Eur J Echocardiogr 2010;11:645-58.
58. Diercks DB, Promes SB, Schuur JD, Shah K, Valente JH, Cantrill SV. Clinical policy: critical issues in the evaluation and management of adult patients with suspected acute nontraumatic thoracic aortic dissection. Ann Emerg Med 2015;65:32-42 e12.
59. Ueda T, Fleischmann D, Rubin GD, Dake MD, Sze DY. Imaging of the thoracic aorta before and after stent-graft repair of aneurysms and dissections. Semin Thorac Cardiovasc Surg 2008;20:348-57.
60. Alric P, Canaud L, Branchereau P, Marty-Ane C, Berthet JP. Preoperative assessment of anatomical suitability for thoracic endovascular aortic repair. Acta Chir Belg 2009;109:458-64.
61. Goshima S, Kanematsu M, Kondo H, et al. Preoperative planning for endovascular aortic repair of abdominal aortic aneurysms: feasibility of nonenhanced MR angiography versus contrast-enhanced CT angiography. Radiology 2013;267:948-55.
62. Lutz AM, Willmann JK, Pfammatter T, et al. Evaluation of aortoiliac aneurysm before endovascular repair: comparison of contrast-enhanced magnetic resonance angiography with multidetector row computed tomographic angiography with an automated analysis software tool. J Vasc Surg 2003;37:619-27.
63. Shaida N, Bowden DJ, Barrett T, et al. Acceptability of virtual unenhanced CT of the aorta as a replacement for the conventional unenhanced phase. Clin Radiol 2012;67:461-7.
64. Karkkainen JM, Pather K, Tenorio ER, Mees B, Oderich GS. Should endovascular approach be considered as the first option for thoraco-abdominal aortic aneurysms? J Cardiovasc Surg (Torino) 2019;60:298-312.
65. Pini R, Faggioli G, Gallitto E, et al. The different effect of branches and fenestrations on early and long-term visceral vessel patency in complex aortic endovascular repair. J Vasc Surg 2020;71:1128-34.
66. Meinel FG, Nikolaou K, Weidenhagen R, et al. Time-resolved CT angiography in aortic dissection. Eur J Radiol 2012;81:3254-61.
67. Wolf F, Plank C, Beitzke D, et al. Prospective evaluation of high-resolution MRI using gadofosveset for stent-graft planning: comparison with CT angiography in 30 patients. AJR Am J Roentgenol 2011;197:1251-7.
68. Abdelbaky M, Zafar MA, Saeyeldin A, et al. Routine anterior spinal artery visualization prior to descending and thoracoabdominal aneurysm repair: High detection success. J Card Surg 2019;34:1563-68.
69. Takagi H, Ota H, Natsuaki Y, et al. Identifying the Adamkiewicz artery using 3-T time-resolved magnetic resonance angiography: its role in addition to multidetector computed tomography angiography. Jpn J Radiol 2015;33:749-56.
70. Nijenhuis RJ, Jacobs MJ, Jaspers K, et al. Comparison of magnetic resonance with computed tomography angiography for preoperative localization of the Adamkiewicz artery in thoracoabdominal aortic aneurysm patients. J Vasc Surg 2007;45:677-85.
71. Tanaka H, Ogino H, Minatoya K, et al. The impact of preoperative identification of the Adamkiewicz artery on descending and thoracoabdominal aortic repair. J Thorac Cardiovasc Surg 2016;151:122-8.
72. Yoshioka K, Tanaka R, Takagi H, et al. Ultra-high-resolution CT angiography of the artery of Adamkiewicz: a feasibility study. Neuroradiology 2018;60:109-15.
73. Amako M, Yamamoto Y, Nakamura K, et al. Preoperative visualization of the artery of Adamkiewicz by dual-phase CT angiography in patients with aortic aneurysm. Kurume Med J 2011;58:117-25.
74. Piacentino F, Fontana F, Micieli C, et al. Nonenhanced MRI Planning for Endovascular Repair of Abdominal Aortic Aneurysms: Comparison With Contrast-Enhanced CT Angiography. Vasc Endovascular Surg 2018;52:39-45.
75. Armerding MD, Rubin GD, Beaulieu CF, et al. Aortic aneurysmal disease: assessment of stent-graft treatment-CT versus conventional angiography. Radiology 2000;215:138-46.
76. Hallett RL, Ullery BW, Fleischmann D. Abdominal aortic aneurysms: pre- and post-procedural imaging. Abdom Radiol (NY) 2018;43:1044-66.
77. Flors L, Leiva-Salinas C, Norton PT, Patrie JT, Hagspiel KD. Imaging follow-up of endovascular repair of type B aortic dissection with dual-source, dual-energy CT and late delayed-phase scans. J Vasc Interv Radiol 2014;25:435-42.
78. Alerci M, Oberson M, Fogliata A, Gallino A, Vock P, Wyttenbach R. Prospective, intraindividual comparison of MRI versus MDCT for endoleak detection after endovascular repair of abdominal aortic aneurysms. Eur Radiol 2009;19:1223-31.

79. Habets J, Zandvoort HJ, Reitsma JB, et al. Magnetic resonance imaging is more sensitive than computed tomography angiography for the detection of endoleaks after endovascular abdominal aortic aneurysm repair: a systematic review. Eur J Vasc Endovasc Surg 2013;45:340-50.
80. Kret MR, Azarbal AF, Mitchell EL, Liem TK, Landry GJ, Moneta GL. Compliance with long-term surveillance recommendations following endovascular aneurysm repair or type B aortic dissection. J Vasc Surg 2013;58:25-31.
81. Javor D, Wressnegger A, Unterhumer S, et al. Endoleak detection using single-acquisition split-bolus dual-energy computer tomography (DECT). Eur Radiol 2017;27:1622-30.
82. Guo Q, Zhao J, Huang B, et al. A Systematic Review of Ultrasound or Magnetic Resonance Imaging Compared With Computed Tomography for Endoleak Detection and Aneurysm Diameter Measurement After Endovascular Aneurysm Repair. J Endovasc Ther 2016;23:936-43.
83. Wieners G, Meyer F, Halloul Z, et al. Detection of type II endoleak after endovascular aortic repair: comparison between magnetic resonance angiography and blood-pool contrast agent and dual-phase computed tomography angiography. Cardiovasc Intervent Radiol 2010;33:1135-42.
84. Zaiem F, Almasri J, Tello M, Prokop LJ, Chaikof EL, Murad MH. A systematic review of surveillance after endovascular aortic repair. J Vasc Surg 2018;67:320-31 e37.
85. Cohen EI, Weinreb DB, Siegelbaum RH, et al. Time-resolved MR angiography for the classification of endoleaks after endovascular aneurysm repair. J Magn Reson Imaging 2008;27:500-3.
86. van der Laan MJ, Bartels LW, Viergever MA, Blankensteijn JD. Computed tomography versus magnetic resonance imaging of endoleaks after EVAR. Eur J Vasc Endovasc Surg 2006;32:361-5.
87. Lookstein RA, Goldman J, Pukin L, Marin ML. Time-resolved magnetic resonance angiography as a noninvasive method to characterize endoleaks: initial results compared with conventional angiography. J Vasc Surg 2004;39:27-33.
88. Sakata M, Takehara Y, Katahashi K, et al. Hemodynamic Analysis of Endoleaks After Endovascular Abdominal Aortic Aneurysm Repair by Using 4-Dimensional Flow-Sensitive Magnetic Resonance Imaging. Circ J 2016;80:1715-25.
89. Salehi Ravesh M, Langguth P, Pfarr JA, et al. Non-contrast-enhanced magnetic resonance imaging for visualization and quantification of endovascular aortic prosthesis, their endoleaks and aneurysm sacs at 1.5T. Magn Reson Imaging 2019;60:164-72.
90. Fearn S, Lawrence-Brown MM, Semmens JB, Hartley D. Follow-up after endovascular aortic aneurysm repair: the plain radiograph has an essential role in surveillance. J Endovasc Ther 2003;10:894-901.
91. Wolf YG, Johnson BL, Hill BB, Rubin GD, Fogarty TJ, Zarins CK. Duplex ultrasound scanning versus computed tomographic angiography for postoperative evaluation of endovascular abdominal aortic aneurysm repair. J Vasc Surg 2000;32:1142-8.
92. Baliyan V, Verdini D, Meyersohn NM. Noninvasive aortic imaging. Cardiovasc Diagn Ther 2018;8:S3-S18.
93. Arko FR, Filis KA, Siedel SA, et al. Intrasac flow velocities predict sealing of type II endoleaks after endovascular abdominal aortic aneurysm repair. J Vasc Surg 2003;37:8-15.
94. American College of Radiology. ACR Appropriateness Criteria® Radiation Dose Assessment Introduction. Available at: https://www.acr.org/-/media/ACR/Files/Appropriateness-Criteria/RadiationDoseAssessmentIntro.pdf. Accessed November 30, 2022.