Modern imaging techniques: applications in the management of acute aortic pathologies

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ABSTRACT
Acute aortic pathologies include traumatic and non-traumatic life-threatening emergencies of the aorta. Since the clinical manifestation of these entities can be non-specific and may overlap with other conditions presenting with chest pain, non-invasive imaging plays a crucial role in their rapid and accurate evaluation. The early diagnosis and accurate radiological assessment of acute aortic diseases is essential for improved clinical outcomes. Multidetector CT is the imaging modality of choice for evaluation of acute aortic diseases with MRI playing more of a problem-solving role. The management can be medical, endovascular or surgical depending upon pathology, and imaging remains an indispensable management-guiding tool. It is important to understand the pathogenesis, natural history, and imaging principles of acute aortic diseases for appropriate use of advanced imaging modalities. This understanding helps to formulate a more appropriate management and follow-up plan for optimised care of these patients. Imaging reporting pearls for day-to-day management can be made.

INTRODUCTION
The aorta is the largest artery in the human body and may be affected by a myriad of acute pathologies. The clinical presentation ranges from asymptomatic (incidentally detected on imaging) to life-threatening emergencies with chest pain being the most common clinical symptom. Acute aortic pathologies encompass acute aortic syndromes (aortic dissection (AD), intramural haematoma (IMH), penetrating aortic ulcer (PAU)), traumatic aortic injury (TAI), pseudoaneurysm, aortitis and postoperative complications. In the last 20 years, there has been an overall global increase in mortality due to aortic aneurysm and AD with estimated deaths increasing to a population of 2.78 per 100 000 in 2010 with maximum mortality increase in men and in developing countries.1 The aortic disease burden is also expected to increase further with an overall increase in life expectancy.

Multidetector CT (MDCT) is the imaging modality of choice for diagnosis of acute aortic pathologies; MRI and ultrasound, though inferior to MDCT due to their limitations in acute setting, can be alternative non-invasive modalities. Increased awareness of the role of various cross-sectional imaging techniques for evaluating acute aortic pathologies is essential for appropriate and time-efficient management that comprises medical, endovascular and surgical approaches. If not acknowledged on time and treated appropriately, acute aortic diseases have very poor prognosis. This review describes the imaging anatomy of the aorta, basic principles of relevant modern imaging techniques and the individual acute aortic pathologies with emphasis on their pathogenesis, imaging features and treatment options.

AORTIC ANATOMY
Based on distinct embryological development, the aorta can be morphologically divided into aortic root, ascending aorta, aortic arch, descending thoracic aorta and abdominal aorta (figure 1). The aortic root extends from the aortic valve annulus to the sinotubular junction and includes the aortic valve, sinuses of Valsalva and origin of the coronary arteries. The ascending aorta extends from the sinotubular junction to the origin of the innominate artery. The aortic arch is the segment between the origin of the innominate artery and the ligamentum arteriosum. The aortic arch gives rise to three major arterial branches in approximately 70% of the population. Proximally to distally, the arch branches are innominate artery, left common carotid artery and left subclavian artery. The common variations of aortic arch branching include the common origin of the brachiocephalic and left common carotid arteries (seen in 20–30% of the population) and the separate origin of the left vertebral artery from the aortic arch (seen in approximately 5% of the population). The descending thoracic aorta extends between the ligamentum arteriosum and the diaphragmatic hiatus while the abdominal aorta extends between the infradiaphragmatic aorta till its bifurcation into common iliac arteries.2 3

IMAGING TECHNIQUES
Multidetector CT
MDCT is often the first line imaging technique among a series of available imaging tools especially in an acute setting. CT is nearly 100% sensitive and specific for diagnosis of aortic pathologies.4 5 A combination of faster gantry rotation, increased ‘z’ axis (or craniocaudal) coverage, improved temporal and spatial resolutions and reconstruction techniques of newer MDCT scanners has significantly improved the image quality. These scanners acquire subcentimeter isotropic voxels that are amenable to excellent reformattting in two
dimensions as well as three-dimensional (3D) volume rendering. CT is also excellent for the identification of anatomical landmarks prior to operative intervention.

Motion artefact within the proximal thoracic aorta due to transmission of cardiac motion is especially pronounced in non-gated scan during cardiac systole and can lead to false positive diagnosis of proximal thoracic AD. This can be prevented by utilisation of ECG gated image acquisition with MDCT that provides motionless imaging of the proximal thoracic aorta with increased accuracy. The ECG gating may be done prospectively or retrospectively. In retrospective gating, the CT images are acquired during the entire cardiac cycle and the best phase is chosen subsequently and reconstructed. To reduce the patient’s radiation dose, retrospective gating is commonly used with mA modulation (tube current modulation). In mA modulation, the tube current is higher during the desired cardiac phase (typically end-diastole) and is very low (usually 5–20%) during the rest of the cardiac cycle (figure 2). This translates to a reduced radiation dose with the advantage of the ability to reconstruct real-time images for valvular/dynamic and functional evaluation along with the assessment of cardiac wall motion. In prospective gating/triggering, the CT scan is acquired during a specific phase of the cardiac cycle, typically during the diastole since it provides relatively motionless aortic root evaluation with improved diagnostic accuracy (figure 3). The end-diastolic thoracic aortic measurements that are done for pre-endograft planning may be associated with smaller aortic diameters when compared with peak systolic aortic measurements. This may lead to undersizing of the endovascular stents causing improper sealing and instability of the stent. The radiation dose to the patient is less in prospective triggering than with retrospective gating. The prime disadvantages of CT include higher radiation dose especially with retrospective gating and the need for the use of iodinated contrast and its associated side effects and complications. Currently, the average radiation dose to a patient from a CT angiography for aortic assessment is 10–15 mSv.

Imaging protocol on CT

The scan for aortic evaluation should extend cranially 3 cm above the aortic arch and caudally to the level of the femoral head as aortic diseases may affect the whole aorta or multiple segments of the aorta.

It is preferable to obtain initial non-contrast non-gated scans of the thoracic aorta especially in patients with suspected acute aortic syndromes since the IMH is best assessed on a non-contrast scan. In patients with suspected ascending aortic pathology, ECG gating should be used on a contrast-enhanced scan whereas a non-ECG gated postcontrast scan is sufficient in patients with suspected descending thoracic/abdominal aortic pathology. Automated tube current dose modulation should be used in a retrospectively gated scan to reduce patient dose. The bolus tracking technique is used to ensure optimal contrast enhancement.

To achieve adequate aortic enhancement, 100 to 125 cc of high iodine concentration contrast medium, preferably 370 mg of iodine per millilitre, is typically used and injected at a rate of 5 cc/s followed by 40 cc of saline flush at 4 cc/s. It is preferable to inject the contrast through the right upper extremity since the contrast in the left brachiocephalic vein may cause extensive streak artefacts that may limit evaluation of the aortic arch and its branches. The CT imaging protocol of our institute is highlighted in table 1.

**Figure 1** Graphical images of thoracic aorta (A) and abdominal aorta (B) showing various levels/landmarks at which the aorta should be measured on CT and MR angiography images.

**Figure 2** Graphical images showing the difference between retrospective ECG-gating with mA modulation and prospective ECG-triggering/gating.

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Magnetic resonance imaging

MRI is the preferred investigation for follow-up of aortic pathologies and diagnosis of non-emergency aortic pathologies. MRI provides better tissue characterisation than CT and allows dynamic imaging without the disadvantage of ionising radiation. The major disadvantages of MRI as compared with CT include longer scan time limiting its utility in critically ill patients, limited availability and increased cost. It is contraindicated in patients with metallic implants like pacemakers, aneurysmal clips, etc.

With the use of vector ECG gating, motionless images of the aortic root can be obtained on MR examinations. As with CT, isotropic imaging of the aorta can be performed with 3D contrast-enhanced MR angiography (MRA) that can be reconstructed subsequently in any plane. Black and bright blood sequences allow comprehensive evaluation of the aortic lumen as well as the wall even without the need for intravenous contrast. However, the use of intravenous contrast is preferred for most MR aorta studies since a 3D contrast-enhanced MRA sequence provides higher spatial and temporal resolutions with 3D reconstructions for accurate diagnosis.

Imaging protocol on MRI

Typical MR protocol for aortic imaging includes initial black blood and bright blood sequences followed by a 3D intravenous contrast-enhanced MR angiography (MRA) that can be reconstructed subsequently in any plane. Black and bright blood sequences allow comprehensive evaluation of the aortic lumen as well as the wall even without the need for intravenous contrast. However, the use of intravenous contrast is preferred for most MR aorta studies since a 3D contrast-enhanced MRA sequence provides higher spatial and temporal resolutions with 3D reconstructions for accurate diagnosis.

Table 1  CT angiography protocol for suspected aortic diseases

<table>
<thead>
<tr>
<th>Aortic CTA protocol at our institute</th>
<th>Scan range</th>
<th>Scan</th>
<th>Gating</th>
<th>Contrast</th>
<th>Contrast dose (depends on eGFR)</th>
<th>Injection rate</th>
<th>Slice thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Above aortic arch till femoral heads</td>
<td>1. Non-contrast ungated chest</td>
<td>Retrospective with minimum dose (100% image acquisition during cardiac diastole and 20% during systole)</td>
<td>Iopamidol 370 mg/mL (Bracco Diagnostic, Princeton, New Jersey, USA)</td>
<td>100 cc (eGFR&gt;60)</td>
<td>4 cc/s</td>
<td>1.5 mm thickness with 1 mm interslice interval</td>
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<tr>
<td></td>
<td></td>
<td>2. Gated contrast-enhanced chest</td>
<td></td>
<td></td>
<td>75 cc (eGFR &gt;30—&lt;60)</td>
<td>Followed by 40 cc saline at 4 cc/s</td>
<td>1 mm thickness with 0.6 mm interslice interval for 3D postprocessing</td>
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<tr>
<td></td>
<td></td>
<td>3. Ungated contrast-enhanced abdomen and pelvis</td>
<td></td>
<td></td>
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</tbody>
</table>

CTA, CT angiography.

Table 2  MR angiography protocol for suspected aortic diseases

<table>
<thead>
<tr>
<th>Aortic MRA protocol at our institute</th>
<th>Scan range</th>
<th>Contrast type</th>
<th>Contrast dose</th>
<th>Sequences</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Chest, abdomen and pelvis</td>
<td>Gadobenate dimeglumine (Multihance, Bracco Diagnostic, Princeton, New Jersey, USA)</td>
<td>0.1 mmol/kg (0.2 mL/kg) at 4 cc/s followed by 20 cc saline at 4 cc/s</td>
<td>1. Axial and coronal ultrafast spin echo (Siemens-HASTE) of chest, abdomen and pelvis</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2. Axial ECG-gated double inversion recovery of chest and abdomen</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3. Single breathhold ECG-gated 3D MRA (sagittal plane) of chest</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4. Single breathhold non-3D MRA (coronal plane) of abdomen and pelvis</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5. Non-gated ultrafast gradient echo post contrast T1 sequence axial and coronal of chest and abdomen/pelvis</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6. Postcontrast double inversion recovery axial (for suspected aortitis)</td>
</tr>
</tbody>
</table>

MRA, MR angiography.
contrast-enhanced MRA sequence. The MRI protocol at our institute is highlighted in table 2. A two-station examination of the thoracic and abdominal aorta is preferred. It provides better spatial resolution and contrast-to-noise ratio. In patients with suspected vasculitis, precontrast and postcontrast black blood sequences help assess the wall thickening and enhancement.

Non-contrast MRI of aorta may be the only sequence possible in patients with severe renal dysfunction, poor intravenous access or severe gadolinium allergy. 3D steady state free precision, time of flight or phase contrast sequences along with black blood imaging (inversion recovery sequences) can be helpful for non-contrast aortic assessment on MRI. Phase-contrast MRI can provide quantitative and qualitative assessment of blood flow.

POSTPROCESSING RAW DATA OF MDCT AND MRI (IMAGE EDITING AND PROCESSING AFTER ACQUISITION)

Centreline and double oblique vessel analysis
After reconstructing the raw data in various planes with thinner slices on the scanner, the data is transferred to a dedicated image postprocessing workstation for reformation and volume rendering as needed. Since the aorta can be tortuous and oblique in course, aortic diameters should always be measured at reproducible anatomical landmarks (figure 1) in a short axis perpendicular to the centreline of the aorta (figure 3) on the 3D workstation for improved accuracy. On CT and MRI, the external diameter of the aorta that includes both walls should be measured as opposed to the internal diameter measured on an echocardiogram.

3D postprocessing
Volume-rendered techniques and maximum intensity projection 3D tools available on the 3D workstation are used for postprocessing after reviewing the axial images. These 3D images complement the source/multiplanar images and should always be interpreted in conjunction with them. Various studies have shown the utility of 3D images for accurate estimation of stenosis and the creation of a vascular map for presurgical planning. While maximum intensity projection provides accurate representation of collateral circulation (in cases of vascular occlusion/severe stenosis), volume-rendered techniques are better for estimation of stenosis and visualisation of the relationship between the area of interest with the rest of the structures. With the help of 3D imaging, aortic aneurysm tortuosity, aneurysm morphology, largest cross-sectional diameter and aneurysm volume can be calculated, all of which have shown to be predictors of aneurysm rupture and need for operative intervention. Also 3D postprocessing is required for comprehensive preoperative planning, especially before endovascular stent repair of abdominal aortic aneurysms.

CT AND MRI IMAGING OF ACUTE AORTIC PATHOLOGIES

Aneurysm
Definition and aetiopathogenesis
An aneurysm is defined as a permanent localised dilatation of the artery, at least 50% greater than the normal luminal diameter of the artery in question. True aneurysms involve all vessel wall layers (intima, media and adventitia). The aortic diameters should always be interpreted in light of the patient’s body mass index, age and gender. Hence setting up a single cut-off point is usually difficult but most institutes consider aneurysmal dilatation of the thoracic and abdominal aorta at diameters more than 4 cm and 3 cm, respectively, irrespective of the body surface area or >27.5 mm/m² for short-statured people (figure 4).

Risk factors associated with the development of aortic aneurysm include genetic disorders (like Marfan syndrome and Loeys-Dietz syndrome), bicuspid aortic valve, hypertension, presence of other aortic pathologies (like dissection or aortitis),
age >65 years, smoking, male sex, family history, hypercholesterolaemia, infection and post-trauma. Most descending thoracic and abdominal aneurysms are atherosclerotic in aetiology whereas a majority of ascending thoracic aneurysms are caused by cystic medial degeneration. Ascending aortic aneurysm can be related to aortic valve disorders but in patients with bicuspid aortic valve, dilatation is not related to valvular dysfunction but to decreased production of fibrillin-1 during embryogenesis causing bicuspid aortic valve as well as wall weakening. The incidence of abdominal aortic aneurysm is lower in the female sex but abdominal aortic aneurysm, when diagnosed in women, carries worse prognosis.

Role of imaging
The primary role of imaging in a patient with aortic aneurysm is diagnosis and assessment of the morphology, the greatest diameter, involvement of visceral branches and complications, and subsequent follow-up. In the same setting, imaging can assist in assessment of significant coronary artery disease or valvular pathologies as it can change the management plan for surgical or minimally invasive repair. Increasing trend is noted towards less invasive endovascular stent repair of non-ascending aortic aneurysms. Endovascular stent repair comes with merits of lower perioperative 30-day mortality, reduced procedure time, shorter recovery time and less intraoperative blood loss but at the cost of higher reintervention rate. In patients having endovascular stent repair, imaging plays a crucial role in comprehensive preintervention planning (figure 5). Imaging provides relevant information on the proximal landing zone, the characteristics of the aneurysm sac (tortuosity and angulation), the distal landing zone, and the vascular access (iliofemoral arteries) for endovascular stent planning. Various inherent imaging features of the aneurysm like proximal aneurysm neck >32 mm, angulation >60°, calcification of >90% of the circumference and extension of aneurysm into bilateral iliac arteries are considered unfavourable anatomical characteristics, and are helpful in deciding the feasibility of open versus endovascular stent repair. Other relevant information on coronary artery anatomy and the intercostal arterial supply to the spinal cord can also be obtained.

Table 3 Class I and Class IIa recommendations on maximal aortic diameter cut-off for treatment of aortic aneurysm in asymptomatic patients

<table>
<thead>
<tr>
<th>Aortic arch aneurysm</th>
<th>≥55 mm</th>
<th>Isolated arch aneurysm (may be planned earlier if adjacent ascending or descending thoracic aortic aneurysm repair is planned)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Descending thoracic aneurysm</td>
<td>≥55 mm</td>
<td>If anatomy is suitable for thoracic endovascular stent repair</td>
</tr>
<tr>
<td>Abdominal aortic aneurysm</td>
<td>≥55 mm</td>
<td>Open/endovascular stent repair</td>
</tr>
</tbody>
</table>

*Coarctation of the aorta, systemic hypertension, family history of dissection or increase in aortic diameter >3 mm/year (measured at the same level)
†Family history of AD, aortic size increase >3 mm/year (measured at the same level), severe aortic or mitral regurgitation or desire for pregnancy.
‡Also indicated if aneurysm growth >10 mm/year.
AD, aortic dissection; BAV, bicuspid aortic valve.

Complications
The single feature of aneurysm that correlates most with chances of complications is maximum aortic diameter. Aneurysm rupture is the most catastrophic complication and is seen on imaging as periaortic haematoma (best seen on non-contrast CT) or active contrast extravasation or high attenuation haemorrhagic fluid collections in the pleura, mediastinum or retroperitoneum (figure 6).

Figure 5 A sixty-six-year-old man with infrarenal abdominal aortic aneurysm. Volume rendered (A) and 3D curved planar reformatted CT images of the abdominal aorta (B–F) showing assessment of various imaging parameters required for pre-endovascular stent planning.
Mycotic aneurysm

Aetiopathogenesis
Mycotic aneurysms occur due to infection of the vessel wall. Staphylococcus and salmonella species are most common pathogens responsible for mycotic aneurysms while rare pathogens include tuberculosis. Infectious agents can reach the artery either by contiguous spread of an adjacent infectious process or by traumatic or iatrogenic implantation. In the thoracic aorta, mycotic aneurysms are more common in the ascending aorta whereas in the abdominal aorta, infrarenal aorta is more commonly involved. Treatment is based on antibiotic therapy and surgical debridement with or without surgical revascularisation.

Imaging
On imaging, mycotic aneurysms are usually saccular with a wide neck, eccentric, or multilobulated with periarterial inflammation and/or air. Imaging may also demonstrate aneurysmal leak and periaortitis haemorrhage (figure 7).

Inflammatory aneurysm
Definition
Inflammatory aneurysms are defined as non-infective aneurysms characterised by inflammatory tissue deposition within the adventitia.

Role of imaging
Inflammatory aneurysms are usually seen in the abdominal aorta and are characterised by the presence of a soft tissue rind around the aorta on cross-sectional imaging (figure 8). The soft tissue thickening may adhere to adjacent retroperitoneal structures (commonly duodenum and ureters) leading to loss of peri-aortic fat planes or mediastinal deviation of ureters. Absence of peri-aortic fluid and air differentiates inflammatory aneurysm from mycotic aneurysms. The differentiation is important since, as opposed to mycotic aneurysm, these are managed by steroids and immunosuppressive drugs. Typically, these aneurysms are less likely to rupture than atherosclerotic aortic aneurysms.

Aortic dissection
Aetiopathogenesis
AD is the most common aortic emergency and is usually related to intimal tears, causing entry of blood into the aortic media, resulting in dissection of media and formation of a double channel aorta. The reported approximate incidence of AD is 2.6–3.5 per 100 000 person-years. Hypertension is the most common risk factor for AD, while the other risk factors include pre-existing aortic diseases, aortic valve disease, family
history of aortic diseases, history of cardiac surgery, cigarette smoking, direct blunt chest trauma and use of intravenous drugs like cocaine and amphetamines.9

Classification and management
AD is classified based on anatomical location (Stanford or DeBakey classification) and time from onset (acute, subacute or chronic).49 50 Dissection is considered acute if the onset of symptoms of suspected AD occurred less than 2 weeks from presentation, subacute between 15 days and 90 days and chronic if the patient presents more than 90 days after symptoms. The Stanford system classifies the dissection into Type A and Type B. Type A, accounting for the majority, affects the ascending aorta while type B affects the descending aorta and/or the aortic arch (figure 9). Stanford classification is more commonly used since it is clinically more relevant. Type A dissections are managed surgically while type B dissections are usually treated conservatively with antihypertensive therapy or by endovascular stent repair unless complicated by end-organ ischaemia or persistent symptoms.50 The randomised trials of INvestigation of STEnt Grafts in Patients with Type B Aortic Dissection (INSTEAD), its extension (INSTEAD-XL) and the International Registry of Acute Aortic Dissection have found no overall mortality benefit, but decreased aorta-specific mortality with thoracic endovascular stent repair as compared with medical management in patients with type B AD.51 52 53 Type A and Type B ADs can result in malperfusion symptoms due to branch vessel obstruction. The branch vessel obstructions can be dynamic or static (figure 10). Recognition of these subtypes is important to formulate the treatment plan. In dynamic obstruction, the vessel arises from the true lumen but the intimal flap prolapses within the origin of the vessel causing obstruction of the vessel origin. Dynamic obstruction is treated with flap fenestration to decrease the pressure within the false lumen thereby decreasing prolapse of the intimal flap. Static obstruction is caused by extension of the intimal flap into the branch vessel and is treated by stenting of the true lumen.54

Role of imaging in management
CT is usually the initial cross-sectional imaging in patients with suspected AD. In patients with AD with calcified intima, non-contrast CT may show internal displacement of calcified intima within the aorta. Non-contrast CT can also suggest periaortic soft tissue from haemorrhage and may identify rupture. On contrast-enhanced scans, the presence of an intimal flap separating the true lumen and the false lumen is the hallmark of AD (figure 11). Demonstration of entrance intimal tear, and identification of true lumen and false lumen are important especially in patients in whom endovascular management is contemplated since the endograft must be deployed in the true lumen and should obliterate the proximal intimal tear.

In classical AD, the true lumen tends to have smaller a lumen with an irregular contour, may show wall calcification and in be continuity with the lumen of the adjacent non-dissected aorta.55 Larger cross-sectional area, slow flow, presence of thrombi and ‘beak sign’ are reliable signs of a false lumen. The presence of

Figure 9 Graphical illustrations showing Stanford and DeBakey classifications of aortic dissection.

Figure 10 Graphical illustrations showing the pathogenesis and treatment plan for two types of branch vessel occlusions in patients with acute aortic dissection.

‘cobwebs’ that are seen as linear low attenuation areas within the false lumen is the most specific but less sensitive sign. In Type A AD, the false lumen typically is along the right anterolateral wall of the ascending aorta and extends distally in a spiral fashion along the left posterolateral wall of the descending aorta. Findings like the size of false lumen, the site of the proximal intimal tear and the retrograde extension of the dissection to the aortic arch should always be highlighted in the report since they impact patient prognosis. The primary entry tear at the concavity of the aortic arch and the short distance between the primary entry tear and the left subclavian artery is associated with more incidence of complications in patients with Type B AD. The identification of potential life-threatening complications such as haemopericardium/pericardial tamponade and identification of any end-organ ischaemia is of utmost importance.

Penetrating aortic ulcer

Definition and aetiopathogenesis
Penetrating aortic ulcer (PAU) refers to ulceration of atherosclerotic plaque that disrupts the intimal layer. PAU accounts for 2–7% of all acute aortic syndromes. It may involve the media and result in IMH or dissection. It may also penetrate through all three aortic layers and form a saccular pseudoaneurysm with subsequent aortic rupture. PAU is commonly located in the descending thoracic aorta and less commonly in the aortic arch and the abdominal aorta.

Role of imaging in management of PAU
On imaging, PAUs typically manifest as irregular crater-like contrast-filled outpouching extending beyond the aortic lumen (figure 12). Extensive background atherosclerotic disease is usually evident. Presence of ulcer diameter >20 mm or neck >10 mm is shown to be associated with rapid disease progression and hence these patients may be considered for early intervention. Besides, various studies have shown the need for aggressive medical management with low threshold for surgical intervention based on clinical or radiological deterioration. If need for intervention arises, symptomatic patients with Type B PAU can be managed with open surgical or endovascular stent repair with encouraging results on using endovascular stent repair. PAU is very rare in ascending aorta but if present, early surgical intervention is usually preferred.

Intramural haematoma

Definition, pathogenesis and classification
IMH is an acute aortic syndrome characterised by the presence of >5 mm thickening of the aortic wall caused either by haemorrhage from vasa vasorum rupture into the medial layer or by medial haemorrhage from penetrating aortic ulcer. IMH represents 10–25% of acute aortic syndromes. Since IMH and classical dissection have identical clinical presentation and risk factors, it is also classified according to the Stanford system of AD classification. IMH can be differentiated from AD by the absence of intimal tear and false lumen. Identification of PAU in patients with IMH is of prognostic significance since patients with IMH with demonstrable PAU have more chances of progression on medical therapy as compared with patients with IMH without demonstrable PAU.

Role of imaging in management
IMH appears as crescentic or circumferential hyperattenuation of the aortic wall (>5 mm) on non-contrast CT scan (figure 13) with displacement of intimal calcification. The differentiation from thrombosed false lumen can be difficult but constant circumferential relationship with the aortic wall of IMH and spiral orientation along the aortic lumen of thrombosed false lumen in AD helps in differentiation. MRI may be used as a...
problem-solving tool if distinction between atherosclerotic wall thickening or thrombus and IMH is difficult on CT. On follow-up CT of patients with IMH, it is important to identify and distinguish intramural blood pool (IBP) and ulcer-like projection (ULP). While IBP is seen as focal contrast pooling within the haematoma which communicates with the intercostal/lumbar artery (figure 14), ULP represents an intimal disruption and is distinguished from IBP by the presence of its widely communicating neck (>3 mm) with the IMH. Differentiation of these entities carry prognostic significance as IBPs are a benign feature whereas ULP is associated with poor prognosis in patients with IMH. Other features that predict poor outcome in patients with IMH are summarised in box 1. The management of IMH is similar to AD (surgical repair for type A and medical management for type B), although long-term prognosis is better for patients with IMH than patients with AD.

Aortitis
Aetiopathogenesis
Aortitis encompasses various aetiologies that lead to inflammation of the aortic wall, the most common of which are giant cell arteritis and Takayasu’s arteritis. While giant cell arteritis usually occurs in patients aged >50 years with twice the incidence in women as compared with men, Takayasu’s arteritis is generally seen in the young population, aged 25–30 years with women affected approximately nine times more compared with men. It is difficult to differentiate these two aetiologies on cross-sectional imaging. Giant cell arteritis has increased wall thickening, higher chances of progression into aneurysm and may show skip areas compared with Takayasu’s arteritis which may show long-segment stenosis due to extensive vascular wall fibrosis. Moreover, giant cell arteritis has a predilection for the thoracic aorta while Takayasu’s arteritis commonly involves the left subclavian artery or the abdominal aorta.

Role of imaging in management
Early imaging findings of acute aortitis include wall thickening and enhancement of aortic wall with periaortic fat stranding and/or visceral branch involvement (figure 15). In the chronic stage, arterial stenosis, occlusion or aneurysm formation is seen. Cross-sectional imaging provides assessment of mural details as compared with conventional angiography that provides only luminal assessment. Various studies have reported >95% sensitivity and approximately 100% specificity of cross-sectional imaging for diagnosis of Takayasu’s arteritis. However differentiation of wall thickening from inflammatory tissue or scar may not be possible on cross-sectional imaging. Metabolic imaging like (18)F-FDG PET/CT holds promise in evaluating treatment response in these patients.

Traumatic aortic rupture
Aetiopathogenesis
TAI is a common cause of death in road traffic accidents with aortic transection accounting for 16% of all deaths from motor

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**Figure 13** A fifty-two-year-old man with a history of hypertension, presenting with acute chest pain. The graphical illustration (A) highlights the pathogenesis of intramural haematoma (IMH). The non-contrast CT image (B) shows a crescentic hyperattenuation within the aortic wall without any intimal flap on contrast-enhanced CT image (C) consistent with IMH. No atherosclerosis or penetrating ulcer was identified, thus signifying rupture of the vasa vasmorum as its possible aetiology.

**Figure 14** A forty-nine-year-old woman with a new finding of intramural blood pool on follow-up CT for intramural haematoma (IMH). A maximum intensity projection (MIP) reconstructed image from contrast-enhanced CT shows focal contrast pooling within the IMH of the descending thoracic aorta that communicates with a right intercostal artery (arrow) in keeping with an intramural blood pool.

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**Box 1 Predictors of complications and poor outcome in patients with intramural haematoma**

**Clinical features**
1. Persistent and recurrent pain despite aggressive medical treatment
2. Difficult blood pressure control
3. End-organ ischaemia (brain, myocardium, bowels, kidneys, etc)

**Radiological features**
4. Ascending aortic involvement
5. Maximum aortic diameter >50 mm
6. Maximal aortic wall thickness >11 mm
7. Enlarging aortic diameter
8. Penetrating ulcer or ulcer-like projection
9. Recurrent pleural effusions
vehicle accidents. A majority of patients with aortic transection die before reaching the hospital while patients with small or partial thickness tear are usually able to reach the hospital. Around 90% of aortic tears occur around the isthmus, as it is the most fixed part of the vessel. Other sites of aortic injury are the aortic arch, the proximal ascending aorta and the aortic hiatus.

Role of imaging in management
Imaging in these patients is very challenging as several other injuries may dominate the clinical picture. CT is the best imaging modality to evaluate TAI due to its wide availability, faster scanning and the capability of providing information about other potential injuries. The direct signs of aortic injury on CT include the presence of intimal flaps, irregular luminal outline, thrombus or debris into the aortic lumen, pseudoaneurysms or frank contrast extravasation (figure 16). In patients with complete rupture, a sleeve of subadventitial contrast is seen. The indirect signs of aortic injury include periaortic haematoma at the level of the isthmus, the haemomediastinum and the haemothorax. A high index of clinical suspicion and early imaging is required for timely management of this lethal injury. In patients with haemodynamic stability, the subacute and chronic aortic transections at the aortic isthmus can be successfully treated by endovascular stent graft rather than by operative repair.

IMAGING OF TREATMENT COMPLICATIONS
Aortic aneurysm repair: endoleak

Definition and aetiology
‘Endoleak’ is defined as persistent blood flow in the aortic aneurysm sac outside the stent graft. Early recognition of this complication after stent graft repair of aneurysm is important since continued leak into the endosac may result in sac rupture. A larger aortic diameter before stenting is a predictor of post-operative endoleak.

Role of imaging in management
CT is the imaging modality of choice in these patients. In addition to arterial phase scanning of the aorta and iliac arteries, a 70–120 s delayed scan should also obtained to identify delayed/slow branch vessel endoleak. Based on the mechanism of leakage, five categories of endoleak are described (table 4). Type I endoleak is an attachment site leak and can be diagnosed immediately after stent deployment during completion angiography. It is important to oversize the stent graft with respect to the reference aortic diameter by 10–15% at the landing zone to prevent stent migration and endoleak. Type II endoleak is the most common type of endoleak (40% of all cases) and occurs mostly via the lumbar or inferior mesenteric artery (figure 17). Type III endoleak is considered a high-pressure leak and warrants immediate treatment. Type IV endoleak usually occurs early after stent placement and is visible until sealing of the graft.

Table 4 Types, mechanism and management of various endoleaks

<table>
<thead>
<tr>
<th>Endoleak subtype</th>
<th>Mechanism</th>
<th>Management</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I</td>
<td>Attachment site endoleak</td>
<td>Stent graft resizing/open repair</td>
</tr>
<tr>
<td>Type II</td>
<td>Retrograde flow through a collateral feeder vessel (commonly inferior mesenteric or lumbar artery)</td>
<td>Follow-up imaging and intervention only if increasing size/symptomatic</td>
</tr>
<tr>
<td>Type III</td>
<td>Fabric tears, graft wall defect or modular disconnection</td>
<td>Immediate repair</td>
</tr>
<tr>
<td>Type IV</td>
<td>Due to graft wall porosity</td>
<td>Benign, intervene only if aneurysm expansion</td>
</tr>
<tr>
<td>Type V</td>
<td>Endotension</td>
<td>Benign, intervene only if aneurysm expansion</td>
</tr>
</tbody>
</table>
fabric by fibrin deposition. Type V endoleak is a diagnosis of exclusion with no discernable cause but results in sac size enlargement over time. The endoleak types and important pearls about their management are summarised in table 4.

Transcatheter aortic valve replacement complications
Percutaneous endovascular prosthetic aortic valve replacement is a relatively new technique for treating severe aortic stenosis in non-surgical high-risk patients. MDCT is an established imaging modality for preprocedure planning as it is important to define aortic root anatomy, annulus measurements, aortic dimensions and morphology of potential access peripheral vessels. Imaging also plays an important role in the identification of various postprocedural vascular complications of transcatheter aortic valve replacement like embolic stroke, vessel dissection, vessel rupture or retroperitoneal haemorrhage (figure 18). The potential risk factors for vascular complications in patients undergoing transcatheter aortic valve replacement include female sex, patients with diabetes mellitus requiring insulin, and patients with high sheath-to-femoral artery and sheath-to-external iliac artery ratios.

FUTURE DIRECTIONS
With newer techniques, the use of imaging for guiding management in patients with acute aortic pathologies continues to grow. Although studied in the context of aortic flow dynamics after left ventricle assist devices, CT images can be processed with computational fluid dynamics techniques to assess haemodynamic parameters such as dynamic pressure and wall shear stress. Theoretically these parameters may provide markers beyond the aortic diameter in predicting the risk of rupture and guiding the appropriate therapy. Similarly 3D phase contrast (4D flow) MRI may be used to calculate peak velocity, pressure

Figure 17 A seventy-one-year-old man, with a status of post endovascular stent repair of infrarenal aortic aneurysm. The non-contrast axial CT (A) image shows large infrarenal aortic aneurysm treated with an intraluminal endovascular stent graft. Maximum intensity projection (MIP) axial contrast-enhanced CT (B) shows a focal area of contrast enhancement (arrow) within the posterior and right lateral aspects of the excluded aneurysm sac that communicates with a lumbar artery consistent with type II endoleak.

Figure 18 An eighty-six-year-old woman, with a status of post-TAVR for aortic stenosis. A post-TAVR conventional catheter angiogram image of the abdominal aortic bifurcation (A) shows active contrast extravasation from the right external iliac artery. The artery was immediately stented, however (B) persistent active contrast extravasation from the right external iliac artery was noted along (arrow) with large retroperitoneal haematoma on subsequently acquired contrast-enhanced CT suggesting inadequate sealing of the leakage site. TAVR, transcatheter aortic valve replacement.

Main messages
- ECG-gating is required for cross-sectional imaging in carefully selected patients with suspicion of ascending aortic pathology.
- There should be consistency in imaging protocol and postprocessing for comparability in follow-up exams.
- Aortic diameters should always be measured in short-axis at specific anatomical landmarks for reproducibility.
- Imaging plays a vital role in the selection of an appropriate management plan for acute aortic pathologies and in preoperative planning.
- The development of newer imaging techniques and postprocessing tools holds promise for further predicting aortic haemodynamic parameters.


**Current research questions**

- Although current guidelines provide cut-off for aortic aneurysm repair based on aortic diameters, will these guidelines change if future multicentre trials based on centreline analysis of the aorta are carried out?
- Will the use of peak systolic diameter instead of end-diastolic diameter in the thoracic aorta impact the overall success of endovascular stent surgeries?
- Will newer endovascular stents that require a smaller landing zone change the current management of aortic aneurysm?
- Will further multicentre trials on aortic diameter cut-off for aneurysm repair in different sexes and ethnicities change current guidelines?

**Key references**


**Self assessment questions**

**Answer true or false for the below.**

1. The term ‘acute aortic syndromes’ includes aortic dissection, intramural haematoma (IMH), penetrating ulcer and unstable aortic aneurysm.
2. MRI with MR imaging is the investigation of choice for acute aortic diseases.
3. Malperfusion syndrome due to dynamic obstruction in a patient with aortic dissection is treated by intimal fenestration.
4. Various clinical and radiological markers can predict prognosis in patients with IMH.
5. Type I and Type III endoleaks are considered ‘treatment failures’ and need intervention.

gradient and wall stress within the aorta that may aid in better understanding aortic pathologies and also help in predicting disease progression.⁹⁹

Dual-energy CT is also helpful in vascular imaging since it provides reduced radiation dose to patients by use of virtual non-contrast images. It also requires a less contrast dose to achieve adequate quality images.⁹⁰ Spectral detector CT is an exciting new addition in cardiovascular CT imaging with several potential applications. It is based on the acquisition of multiple spectrally distinct attenuation data sets and thus distinguishes tissues with different attenuation at different photon energies. Recent studies have shown its application in artefact reduction, boosting of intravascular contrast in suboptimal enhanced contrast studies and differentiation of slow flow from the thrombus.⁹¹ ⁹² Though these techniques hold promise, prospective studies are required to establish the validity of these novel techniques.

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**References**


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