Traditionally, radiological imaging of the human body has been limited to a two-dimensional depiction of a three-dimensional reality. For the thoracic aorta modalities most commonly used were plain (chest) radiography, (digital subtraction) angiography and single-slice computerized tomography (CT). Over the last decade, tremendous technical advancements have been made in various imaging modalities. The speed of data acquisition with CT scanning and MRI has increased, thus enabling fast, high resolution axial imaging. The concurrent development of advanced three-dimensional volume-rendering techniques, that require high computational speed, allowed for the development of CT angiography, MR angiography and 3-D rotational angiography (3-D RA). In this chapter, a brief overview on the technical aspects of the currently available modalities will be given and advantages and disadvantages of each technique will be discussed. The radiological anatomy of the thoracic aorta and its branches as depicted with these new imaging techniques will be described in detail.

Imaging modalities

For successful evaluation of vascular pathology in general, an imaging study must enable accurate measurements, demonstrate intraluminal abnormalities and mural disease, and depict (patency of) side branches [1]. Evaluation of vascular disease is facilitated by three-dimensional techniques, and improves appreciation of the geometry of vascular structures and lesions. The currently available imaging modalities that allow for three-dimensional evaluation of the thoracic aorta are multi-detector row CTA, dual source CT, contrast-enhanced MRA, 3D-RA and cone-beam CT.
**Multi-detector row CTA**

As compared to single-slice CT, scanning speed of multi-detector row CT has increased a 40-fold, which makes it possible to scan the entire thorax in a short breath-hold. The present generation of multi-detector row or multi-slice CT scanners allows for a simultaneous acquisition of up to 64 slices, while in the near future, systems with over 256 detectors will become available. With a multi-detector row CT, a single acquisition yields a volume of data, instead of a number of slices (as is the case when using helical CT). Thus far, resolution in the z-axis “slice thickness” was still a limiting factor in image quality for multiplanar reconstruction (MPR). With an increase of the number of detectors, resolution increases as well, and thus (near) isotropic imaging becomes possible (i.e. imaging with a resolution that is equally high in all directions).

It has been demonstrated that in order to get optimal enhancement of the thoracic aorta preferably high-concentration contrast should be used (> 300 mg I/mL), followed by flushing with a saline bolus [2-4]. Scan delay can be optimized, and contrast medium dosage can be reduced by using a test bolus technique, or using a automatic bolus recognition system (bolus triggering) [3]. Scanning protocols vary with different systems and manufacturers. With a four-row detector most examinations are performed with 2.5 mm collimation and a table speed of 15–20 mm per rotation, while using a 16-row detector collimation is reduced to 1.5 mm, and table speed can be increased to 36 mm per rotation. Contrast is injected at a flow-rate of 3–5 mL/s, for a total volume of 120 mL. In a typical protocol for 64 slice CT scanning, a bolus of intravenous iodine contrast is given via a power injector in the right antecubital vein. After injection, the indwelling catheter is flushed using a bolus of 20–50 mL saline fluid to push the contrast bolus forward. A region of interest (ROI) marker is placed in the ascending aorta. When the contrast-enhancement reaches 100 HU in the ROI the scanner is triggered and data acquisition commences. Images are acquired at 0.6–1.25 mm slice thickness a pitch of 1.0–1.5 and a reconstruction interval of 0.5–0.625. Radiation dose for CT angiography is at least 2–3 times lower as compared to the dose for angiography [5].

Anatomic coverage should include the thoracic inlet (in order to evaluate congenital anomalies of the supra-aortic arches), and the diaphragm (that can help determining the side of the descending aorta) [5].

Three-dimensional volume-rendering techniques permit real-time, interactive evaluation in any plane and projection. This enhances understanding of vessel dilatation, mural thrombus and branch vessel anatomy, and further allows visualization of both vascular structures and adjacent viscer and airways [1,5].

After obtaining the volumetric data set, a number of post-processing image reconstruction options are available [5]:

- multiplanar reconstruction (MPR): two-dimensional sections with a thickness of one voxel (fast, easily performed at the CT-scanner);
- variable-thickness displays consisting of an assimilation of various sections;
- maximum-intensity projection (MIP) in which images are derived by projecting the highest attenuation voxel in a ray through the scan volume onto an image plane; vessels running in close proximity of osseous structures or calcifications can be easily obscured;
- shaded surface display; this method uses a single threshold to choose relevant (high-density) voxels; because of the threshold this method is susceptible to artifacts, and may fail to demonstrate vascular calcifications;
- three-dimensional volume rendering techniques (VRT; requires separate workstation); each voxel is adjusted to opacity, color, and brightness according to each CT value, according to preset color and opacity maps; the advantage of this technique is that no threshold levels are being selected, thus avoiding the possibility of altering apparent diameters of vessels [6].

Reversing window-level transfer function, virtual angioscopic images can be produced [7,8]. In summary, the advantages of multi-detector row CT include shorter imaging time, greater axial coverage, motion artifact suppression, improved z-axis resolution, higher axial spatial resolution, decreased total dose of iodinated contrast, and real-time interactive three-dimensional display facilities on workstations.

The development of fast multi-slice CT scanners and advanced post-processing tools has expanded the prospects of CTA. One of the most interesting new applications is dynamic CTA. Acquisition can be synchronized to patients electrocardiogram in order to minimize the artifacts caused by heart movements. A possible drawback of dynamic CTA is the alleged increased radiation dose. However, retrospective EKG gated dynamic CTA is based upon conventional multi-slice CTA. Radiation dose and acquisition parameters are therefore similar to conventional CTA. By fusing CTA data with EKG-information, dynamic CTA results in the reconstruction of images for different phases of the cardiac cycle. This provides valuable information on aortic pulsatility and dynamic changes in aortic morphology [9,10].

The latest development in CT-scanning is dual source or dual energy CT-imaging (DS-CT). As X-rays penetrate the body, radiation energy is attenuated. The degree of attenuation depends upon the strength/energy of the X-ray beam and the tissue examined. High energy X-rays will show bone structures only as they pass freely through soft-tissue. Conversely, low-energy radiation allows the identification of different types of soft-tissue. The gantry of a dual source CT-scanner features two X-ray tubes independently transmitting at different energy levels (typically 140 kV and 80 kV). This allows...
the differentiation of various tissue types during one gantry rotation. DS-CT holds great promise for radiation dose reduction during TEVAR follow-up. Current follow-up regimes often require a combination of non-enhanced CT, contrast-enhanced CT and delayed phase CT. By using contrast-enhanced DS-CT and post-processing software virtual non-enhanced CT images can be reconstructed. The software evaluates the 80 kV and 140 kV images and quantifies the iodine content of each voxel. By subsequent removal (subtraction) of iodine, the virtual non-enhanced images are calculated [11]. DS-CT might therefore reduce radiation dose by 44%–61% [11–14]. The technique may also allow for reduction of the total amount of contrast used, due to the better attenuation of contrast at a low energy acquisition. Main limitations of the virtual non-contrast images are caused by erroneous calcium subtraction and higher image noise (leading to lower image quality) [14].

Besides developments in scanner hardware, the field of image fusion is rapidly developing and might confer several benefits with regard to endografting for complex aortic aneurysms. One exiting field is the use of preoperative imaging as a tool during the endografting procedure itself. By synchronizing the preoperative CT with the live angiographic view in the operating room, a three-dimensional roadmap can be generated in which the vessels can be navigated. This might alleviate catheterization of target vessels in tortuous anatomy and allow for more precise deployment of fenestrated or branched endografts. The sometimes critical errors in deployment or very lengthy radiation exposures might then be avoided.

A second example of CT based image fusion is integrated positron emission and computed tomography (PET/CT). PET/CT relies on the increased uptake of radioactive labelled glucose (FDG) in metabolically active (inflammatory) cells. After intracellular accumulation, FDG disintegrates resulting in positron and gamma ray emission easily detected by cameras surrounding the patient. By combining and fusing images of positron emission and computer tomography (FDG-PET/CT), the exact location of increased metabolic activity is depicted [15]. This technique may be useful to identify increased metabolic activity related to infection or vasculitis [16].

MR angiography

Traditionally, MRI imaging, using T1-weighted spin-echo (black blood) imaging and cine-MRI imaging is well suited for evaluation of the gross anatomy of the thoracic aorta, as well as evaluation of pericardial, pleural and mediastinal effusions [17]. Flow-based methods of imaging (using time-of-flight (TOF)) or phase contrast (PC) properties yield bright blood images using gradient echo techniques [18]. Limitation of the latter techniques, however, is that they rely on the physical properties of flowing blood (velocity, direction etc.), making the technique susceptible for artifacts, that may result in over-estimation of stenoses or even a false diagnosis of occlusion of a vessel. Furthermore, the spatial resolution and signal-to-noise ratio provided by these two-dimensional techniques do not allow evaluation of small vessel lesions or small side branches [19].

The most-suited technique currently used in the evaluation of thoracic aortic anatomy and disease is dynamic subtraction magnetic resonance angiography (MRA), using Gadolinium (0.2 mmol/kg, flow rate of antecubital injection 2 mL/s) as intravenous contrast agent [18,20–24]. Gadolinium shortens the T1 of blood, and therefore allows shorter imaging times. Thus, less flow related and motion related artifacts occur, and therefore the technique can demonstrate subtle aortic lesions such as penetrating ulcers, and small intercostal arteries. After a plain MRI, intravenous contrast is administered. Using bolus timing (either by using a test bolus or real-time fluoroscopic triggering), the arrival of the contrast can be timed, and the contrast-enhanced sequence is performed [18,25]. This is followed by subtraction of the two series. Limitation of this test-bolus technique is the potential for diminished artery-to-vein contrast, associated additional cost of test-bolus contrast and the potential difficulty to observe the test-bolus in distal vessels or in cases with slow flow [25]. To further reduce respiratory motion artifacts and artifacts related to cardiac motion and pulsatile flow, electrocardiographic triggering techniques can be used [17,26]. The thus obtained images can either be viewed on a slice-to-slice basis, or can be reconstructed on a computer workstation into a maximum intensity projection (MIP-image). The appearance of MIP reconstructions resembles that of conventional angiography, and is therefore useful in planning of surgical procedures [21]. Using three-dimensional reconstruction techniques, it is also possible to obtain an internal view of the vessel and its walls (virtual intra-arterial endoscopy) [21]. It is of importance to evaluate both source images and reconstructed images, in order to optimize diagnostic yield (e.g. a dissection can be easily overlooked evaluating MIP images alone) [26]. The lack of clinically significant nephrotoxic effects (also at higher intravenous dosage of Gadolinium) makes contrast-enhanced MRA the modality of choice for vascular imaging in patients suffering from renal insufficiency. However, recently some issues were raised regarding the occurrence of a syndrome of nephrogenic systemic fibrosis, that might limit the applicability of CE-MRA in patients with renal insufficiency [27]. Furthermore, MRA does not suffer from interference (blooming artifacts) from high-signal non-arterial structures that are analogous to bone (calcification) at CTA [28], and is therefore able to differentiate between total occlusion and high-grade stenosis of for example, the supra-aortic arteries. Further, refinements can be made using the newer so-called blood-pool contrast agents (either ultra small particle iron oxide [USPIO], or Gadolinium-based blood-pool agents [Gadofosveset]) which will increase sensitivity even more. These contrast
agents offer the possibility to perform high resolution imaging in late phase (over 1 hour for Gadofosveset and 24 hours for USPIO), and still allow for arterial phase (first pass) imaging, using a relatively low dose of contrast. This allows for longer scanning times, and thus higher resolution images can be obtained with isotropic resolution of 0.6 mm [29].

Future applications of MR imaging

As mentioned above, Gadolinium and iron based blood-pool agents have been developed. USPIO is composed of ultrasmall superparamagnetic particles of iron oxide. Due to the magnetic properties of the contrast, accumulation results in marked signal loss (blackening) on iron-sensitive MR sequences. After intravenous injection, the particles slowly migrate from vascular to interstitial space to be internalized by macrophages [30]. Because of this slow migration, plasma half-life is long resulting in a blood-pool effect. Besides this potential benefit for the detection of endoleak, the cell-specificity for macrophages results in a wide variety of new applications, including the non-invasive identification of macrophages in vulnerable atherosclerotic plaques [31]. A pilot study by Kooi et al. showed USPIO uptake in atherosclerotic plaques of the carotid artery and Howarth et al. focused on the differential uptake of USPIO in symptomatic and asymptomatic atherosclerotic plaques [32,33]. Like rupture prone vulnerable atherosclerotic plaques, aneurysm rupture is characterized by extensive inflammation of the arterial wall [34]. However, in spite of the potential of USPIO-MR as a possible selection tool for prophylactic aneurysm repair, present literature on USPIO uptake in the aortic wall is limited and future studies will be directed at the predictive value of USPIO uptake for aneurysm growth and rupture [35]. Like dynamic CTA, dynamic or cine MR imaging uses cardiac gating to create images for every given phase of the cardiac cycle. Repeating the acquired images in the correct sequence results in an endless cine loop, creating the impression of a movie. Like dynamic CTA, cine MR has been studied extensively to identify dynamic changes in aortic dimensions during the cardiac cycle.

Scanning parameters may vary depending on type and manufacturer of the MRI system, and will not be listed here.

Angiography

Digital subtraction angiography (DSA)

Compared to conventional angiography, digital subtraction angiography (DSA) significantly reduces examination time, contrast material load and patient discomfort [36]. DSA allows an accurate assessment of aortic sidebranch patency crucial for the selection, production and deployment of conventional and tailor-made branched or fenestrated endografts [37]. DSA also facilitates adjunctive endovascular procedures in patients with adverse aneurysm or access artery morphology.

To facilitate the safe introduction of aortic stent-grafts through diseased iliac arteries, a relining and dilating of stenosed iliac arteries is sometimes necessary. In very narrow vessels, serious complications as a result of access-related damage to the iliac arteries can be prevented by covered endografts by a “paving and cracking technique” [38]. Aorto-iliac aneurysms sometimes require fluoroscopy controlled coil embolization of the internal iliac artery to allow safe endograft coverage of the internal iliac artery orifice.

The main limitation of DSA is that it fails to visualize mural thrombus, compromising diameter measurement and landing zone assessment that can be particularly misleading for EVAR. CT or MR imaging has therefore replaced DSA as the primary imaging study for preoperative EVAR planning [39]. With the ongoing development of non-invasive imaging modalities like CT and MR and their image post-processing tools, the preoperative use of DSA is extremely limited, especially since DSA is still associated with a small but distinct risk of complications [40].

Three-dimensional rotational angiography (3D-RA) and cone-beam CT

Conventional rotational angiography, is obtained by performing a motorized movement at constant speed of the C-arc around the patient during continuous contrast injection. To obtain three-dimensional images from a conventional rotational angiographic run, two methods exists. One consists of an examination in two phases, where at first the C-arm makes a sweep acquiring images that act as a mask for the subsequent data acquisition. Subsequently, a return sweep is performed while contrast is injected throughout the entire period of data acquisition [41,42].

The other technique of obtaining 3D-RA is directly based on conventional rotational angiographic images without the use of subtraction [43–45].

With both techniques, images are transferred to a workstation, where they are converted into pseudo-computed tomography slices (the image intensifier being considered a multi-line detector). Using specific algorithms, that correct for image intensifier and contrast distortion, the data set is reconstructed into a volume-rendered image. During this reconstruction process, two different types of image correction are performed to limit visual distortion to a minimum: pincushion distortion correction that is used for diminishing of the environmental influences caused by the earth magnetic field and the isocenter correction that corrects all the movement imperfections introduced by the rotating C-arc [46]. The three-dimensional volume obtained in this way can be rotated and viewed in any direction, and optimal tube positioning (angulation, skew) can be chosen. Determination of vessel geometrical properties (length, diameter) can be done manually or using automated vessel analysis (AVA) software. The latter software can also provide an endoscopic view (virtual angioscopy), used for evaluation of the vessel interior. Recent developments in soft-
ware, using an unenhanced and a contrast-enhanced run also allow visualization of calcifications. The same method can provide an improved depiction of stent location and its relation to the calcified plaque and vessel wall. Important information on flow characteristics, can be gathered from the cinefluoroscopic angiographic images.

A disadvantage of the 3D-RA technique is non-visualization of thrombus. The same is true for conventional angiography. Calcification, however, can be demonstrated using 3D-RA (using either the source images) showing some indirect signs of the presence of thrombus can be present (discrepancy between angiographic lumen and location of calcification), or the calcified plaque software. Recent software developments and use of flat panel detectors allow for so-called soft-tissue imaging, which yields images similar to CT. In fact, the rotating X-ray tube and flat panel detector can be considered to be a CT scanner. This technique of so-called cone-beam CT (XperCT, DynaCT, InnovaCT) uses a wider beam of X-rays as compared to the classical (multi-detector) CT scanners, in combination with all the individual detectors of the flat panel detector. For this reason, a higher spatial resolution can be obtained (28 line pairs/cm for cone-beam CT as compared to 16 line pairs/cm for CT). The XperCT protocol consists of 621 projections of 1024 × 792 pixels at the 30 × 40 cm zoom format (0.370 mm pixel pitch). The images are acquired at 30 frames per second, in 20.7 seconds. A low-dose protocol acquiring 312 images in approximately 10 seconds is also available. Disadvantage of the cone-beam CT technique is the lower contrast resolution and an increased susceptibility to beam hardening artifacts and “noise”.

The volume as obtained with cone-beam CT can also be used to guide needle-assisted procedures (XperGuide, SynGo I-guide). This navigational tool creates an overlay of live fluoroscopy and three-dimensional soft-tissue imaging that provides information on the planned needle path from entry point to target. Changes to the live fluoroscopy following adjustment of X-ray/detector distance, position and/or magnification are transferred to the three-dimensional reconstruction so that the matching is maintained throughout the procedure. Guidance graphics are superimposed onto the fluoroscopic data, and it is possible to superimpose the graphics onto slice data or volume data, thus achieving a better understanding of the needle position with respect to the surrounding soft-tissue structures that are not visible on the fluoroscopic images.

Main use of 3D-RA is in a therapeutic setting in the interventional suite. Use as a diagnostic modality in cases with complex anatomy is another field of application of 3D-RA. The major advantage of 3D-RA is that due to the short reconstruction times the physician can optimize projection, and make adjustments during the interventional procedure, in order to ensure optimal outcome, without additional procedure time. Table I lists advantages and disadvantages of the various three-dimensional imaging techniques.

**Gross anatomy**

The thoracic aorta starts at the level of the aortic valves in the right anterior mediastinum. The aortic root is formed by the three sinuses of Valsalva. Evaluation of the (stenotic) aortic valve using CT has attained (renewed) attention over the last years. Evaluation of the left ventricular outflow tract, and the size of the aortic root is of importance in determining the feasibility of transarterial or transapical aortic valve repair (revalving) (**figures 1 and 2**).

The ascending thoracic aorta then follows an upward and subsequent left laterodorsal course through the thoracic cavity and is continuous with the aortic arch. The aortic arch has the shape of a semicircle, and slightly ventral to the vertex it gives off it’s three largest branches (brachiocephalic trunk, left com-

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Figure 1

a: axial CT at level of aortic sinus (arrow); the trilobar appearance is clearly appreciated; part of the main stem of the left coronary artery is clearly seen (arrowhead); b: axial CT at a slightly lower level as (a) demonstrating the origin of the right coronary artery (arrow); c: axial CT at a level below (b), depicting cusps of aortic valves (arrow); d: axial CT at level of common trunk of pulmonary artery (asterisk), demonstrating site of anastomosis (arrow) of aorto-coronary bypass graft (arrowhead); e: curved reformatted MPR demonstrating full course of bypass graft (arrow); f: VRT image depicting aorto-coronary bypass graft to advantage (arrow)

Figure 2

a: para-axial MPR of CTA demonstrating left ventricular outflow tract; b: para-sagittal MPR of CTA demonstrating left ventricular outflow tract
mon carotid artery and left subclavian artery). Finally, it makes a downward turn as the descending thoracic aorta. The transition of the aortic arch to the descending thoracic aorta lies at the level of the isthmus (insertion of the ligamentum arteriosum, the remainder of the ductus Botalli). At the level of the diaphragm the aorta starts its abdominal course. The diameter of the thoracic aorta normally measures 3.3 cm at the aortic root, 3.0 cm at the mid-ascending portion, 2.7 cm at the level of the aortic arch, and 2.4 cm at the proximal descending aorta ([47] (figure 3).

Along the course of the thoracic aorta, several side-branches originate, that are described below.

**Coronary arteries**

The left main coronary artery arises from the left posterior Valsalva sinus and divides into the left anterior or descending artery running to the left of the common trunk of the pulmonary artery and the left circumflex artery (following the left atrio-ventricular groove). The right coronary artery originates from the right anterior coronary sinus, caudally from the left coronary artery and prior to giving of its first branch (conus artery), it runs rightward posterior and inferiorly. With optimization of spatial resolution, decreasing scanning time and proper cardiac gating, these four main coronary arteries can be visualized using CT ([48,49] and MRI [50] (figure 4).
Supra-aortic vessels
The first and largest branch is the innominate or brachiocephalic artery, which arises from the commencement of the aortic arch. It divides into the right subclavian and common carotid artery. The brachiocephalic trunk is bordered by the right innominate vein and pleura on the right side, and is crossed in front by the left brachiocephalic vein. Initially, the course of the brachiocephalic trunk is in front of the trachea, and than to the right of it. The second branch is the left common carotid artery that arises slightly to the left of the brachiocephalic trunk. It extends upward, at first in front and then to the left of the trachea.

Finally, the left subclavian artery arises from the aortic arch, behind the left common carotid artery, and ascends lateral to the trachea (figures 5–8).

Intercostal arteries
In most patients, there are nine pairs of intercostal arteries that originate from the posterior aortic wall along the lower nine intercostals spaces [51]. In general, the orifices of the left and right intercostal arteries located in close proximity to each other (figure 9).

Anterior spinal artery
The most important arterial feeding vessel of the thoracolumbar part of the spinal cord is the most dominant of the anterior radiculomedullary arteries (also known as the great anterior radiculomedullary artery or artery of Adamkiewicz). This artery arises from the radiculomedullary artery, that is a division of the posterior branches of intercostal and lumbar arteries. The distal portion of the great anterior radiculomedullary artery forms a characteristic “hairpin” turn. The artery originates in 68–73% of cases from left intercostal or lumbar arteries, with the level of origin ranging from the level of the ninth intercostals to the second lumbar artery (in 62–75% of cases at the 9th–12th intercostal artery) [52,53]. Using meticulous technique, the artery of Adamkiewicz can be visualized in 66.7%–69% using MR angiography, and in 68–90% using CTA [52–55] (figure 10).

Bronchial arteries
Almost all bronchial arteries originate from the thoracic aorta between the level of Th 4 and Th 7 [51]. There are usually two bronchial arteries supplying the right. The first commonly arises from the descending aorta as a common intercostobronchial trunk with the third right posterior intercostal artery, and has a posterolaterally lying orifice. The second important artery is the common right and left bronchial artery, that arises from the
Imaging of the thoracic aorta

**Figure 7**
a: 3D-RA; cinefluoroscopic image of selective injection into brachiocephalic trunk; b: 3D-RA; reconstructive zoom with measurements (yellow arrows) of brachiocephalic trunk distally from stenosis at its origin (white arrow); green, red, and blue arrows indicate orientation of x, y, and z-axis; c: 3D-RA; cutplane (red) indicating plane of cross-section used for measurements.

**Figure 8**
a: axial CT in patient after deceleration trauma, demonstrating extravasation of contrast medium at level of aortic arch (arrow); b: sagittal oblique MPR demonstrating aortic rupture at inner curve of aortic arch, at level of isthmus (arrowhead); c: sagittal oblique MPR slightly lateral from slice shown in (b), showing extension of rupture (arrowhead); d: VRT image demonstrating semicircular extension of rupture to advantage (arrowhead); e: VRT image with cutplane running through aortic arch (same level as MPR in b), demonstrating contrast extravasation (arrowhead); relationship to supra-aortic vessels can clearly seen (asterisk = left subclavian artery); f: VRT image with cutplane perpendicular to aortic arch; semicircular extension of contrast extravasation (arrowhead).
**Figure 9**

a: MRA; MIP reconstruction demonstrating lower intercostals arteries (arrowheads); b: sagittal MPR; descending thoracic aorta (asterisk) with several intercostal arteries (arrowheads); c: sagittal MPR; descending thoracic aorta with several intercostal arteries (arrowheads); note presence of (false) aneurysm at the level of the aortic isthmus (asterisk), after angioplasty of aorta for aortic coarctation

**Figure 10**

a: CTA, curved reformatted MPR demonstrating course of anterior spinal artery (arrowheads); b: CTA, curved reformatted MPR demonstrating typical hairpin loop of proximal segment of anterior spinal artery (arrowhead)
anterior surface and supplies both lungs. On the left side, a separate left bronchial artery is usually present, and arises from the anterolateral surface of the aorta. Many variations occur, including origins from the internal thoracic artery, left subclavian artery and inferior thyroid artery (figure 11).

**Congenital variants and abnormalities**

**Coronary arteries**
The most common congenital anomalies are a left circumflex artery arising from the right coronary artery or right sinus and separate origins of the left circumflex and left anterior or descending artery from the left coronary sinus. Right coronary aneurysms (either congenital or acquired) can be clearly depicted using three-dimensional techniques, thus aiding surgeons in preoperative planning [48,56]. The aortic sinus itself can also demonstrate aneurysmal degeneration, that can be depicted using three-dimensional imaging techniques [26]. Finally, three-dimensional techniques can be used to demonstrate aorto-coronary bypass grafts.

**Supra-aortic vessels and aortic arch**
The normal aortic arch configuration with brachiocephalic trunk, left common carotid and left subclavian artery is seen in about 70% of patients. The most frequent variant is a common origin of the brachiocephalic and left common carotid artery (a so-called bovine trunk). The second most frequent variation is a left vertebral artery, directly arising from the aorta; other but less common (< 1%) variants are common origin of both common carotid arteries, the presence of two brachiocephalic arteries and finally a separate origin of all four great vessels [51] (figures 12–14).
**Figure 12**
a: axial CT in patient with type-A dissection; intimal flap is clearly seen (arrowhead); b: axial CT in same patient at level of origin of supra-aortic vessels, demonstrating common origin of innominate and left common carotid artery (bovine trunk; asterisk); c: coronal MPR, demonstrating extent of intimal flap (arrow) with calcification; flap limited to ascending thoracic aorta; d: coronal MPR; bovine trunk clearly depicted (asterisk); e: sagittal oblique MPR demonstrating dilation of ascending thoracic aorta, origin of supra-aortic vessels and aneurismal changes in descending thoracic aorta; f: VRT image; depiction of intimal flap (arrow) in ascending thoracic aorta.

**Figure 13**
a: sagittal oblique MPR of CTA demonstrating bovine trunk; previous stenting of left common carotid artery and left subclavian artery; b: VRT of the same patient in b.
The most common malformation of the aortic arch is a left aortic arch with an aberrant origin of the right subclavian artery (arteria lusoria). In this type of malformation, the right subclavian arises distally from the left subclavian artery and right and left common carotid artery. Another common anomaly is the presence of a right aortic arch, in which the ascending thoracic aorta arches posteriorly to the right side of the trachea and esophagus. Vascular rings are characterized by encirclement of the trachea and esophagus by the aortic arch and associated structures. Vascular rings are the result of an abnormal embryologic development of the paired fourth aortic arches, in which primitive aortic arches fail to fuse or regress normally. Typically, each embryonic arch gives rise to their respective common carotid artery and subclavian artery. Normally the embryonic right arch regresses, while the left aortic arch persists, resulting in a left-sided aortic arch and great vessels. When the left embryonic arch regresses, the result is a right aortic arch, while failure of either of both arches to regress results in a double aortic arch. The most common (symptomatic) vascular rings are associated with a complete double aortic arch, an incomplete double aortic arch with an atretic portion, a left aortic arch with an aberrant right subclavian (arteria lusoria, see above) and a right aortic arch with an aberrant left subclavian artery. Three-dimensional reconstructions of CT and MRI images can obviate the need for diagnostic angiography. Imaging
**Figure 17**

a: 3D-RA; default reconstruction in a patient with double aortic arch; smaller ventral arch (arrowhead) and larger posterior arch (arrow); b: 3D-RA; reconstructive zoom, more clearly depicting separate origin of left and right subclavian and both common carotid arteries (absence of brachiocephalic trunk); c: 3D-RA; true cranio-caudal view depicting double arch to advantage.

**Figure 18**

a: MRA; MIP reconstruction in patient with false aneurysm (asterisk) at level of aortic coarctation (treated with PTA in the past [arrow]); b: MRA; MPR-reconstruction showing distal extent of false aneurysm (asterisk); c: CTA; VRT image demonstrating narrowing of the aorta distally from the origin of the left subclavian artery; aortic coarctation (arrowhead); d: MRA; MIP reconstruction of another patient with more distally located aortic coarctation (arrowhead).
**Figure 19**

a: axial CT at the level of the carina (asterisk), in a patient with widening of the descending thoracic aorta and an intimal flap (arrowhead); type B dissection; b: coronal MPR in the same patient, depicting larger diameter false lumen (asterisk) and small diameter true lumen (arrow); note difference in enhancement with higher density in the, high-flow, true lumen; c: para-sagittal MPR of CTA in patient with type B dissection; the false lumen (arrow) and true lumen (black dot) can be easily differentiated; the right renal artery is perfused from the true lumen; d: coronal MPR of CTA in same patient as 19c demonstrating perfusion of left renal artery (arrowhead) from true lumen (black dot)

**Figure 20**

a: sagittal oblique MIP from MRA; dissection flap (arrow) in distal descending thoracic aorta; b: sagittal oblique MIP from MRA; extension of intimal flap in aortic arch (arrowhead) and left subclavian artery (arrow); patient with type B dissection with secondary extension into type A
studies should be evaluated for aortic position, coarctation, vascular compression of airways, collateral vessel formation and aortopulmonary shunts [6].

Aortic coarctation

One of the most common congenital cardiovascular lesions, defined as a congenital narrowing of the aorta characterized by stenosis of the juxtaductal aorta (i.e. at the ductus arteriosus just distal to the origin of the left subclavian artery) [58]. Three-dimensional Gadolinium-enhanced imaging is helpful in determining coarctation severity by demonstrating collateral vessels (e.g. intercostals and bronchial arteries), that are indicative of the hemodynamic significance of the lesion, while black blood images can demonstrate

![Figure 21](image1)

Figure 21

a: sagittal oblique MPR of CTA; aortic dissection with entry tear (arrowhead) distally from the origin of the left subclavian artery; note presence of subintimal hematoma; b: axial CTA image of the same patient demonstrating extension of subintimal hematoma (arrowheads) and entry tear (arrow); c: axial CTA image of the same patient at a lower level showing extension of the subintimal hematoma towards the aortic root (arrow) and pericardial space (arrowhead)

![Figure 22](image2)

Figure 22

a: coronal MPR of CTA in patient after aortic arch replacement for type A dissection with so-called elephant trunk; the prosthetic graft (arrowhead) can be seen extending into the (dilated) descending thoracic aorta; b: axial CTA image demonstrating elephant trunk (arrowheads)
Acquired aortic disease

**Dissection**

MRI and CT angiography are established techniques in the assessment of aortic dissection, and is able to classify dissection according to the DeBakey or Stanford classification [17]. Detection of the intimal flap is best done using contrast-enhanced MRA or CTA [5] (figures 19–22). High signal intensity/density within the false and true lumina is a finding consistent with patency, and allows for visualization of the intimal flap; in general the true lumen has a higher density/signal intensity than the false lumen, owing to faster flow [18]. Delayed phase imaging can be used to depict the false lumen better [19]. The precise extent of an intimal flap and its relationship to the arch vessels can be clearly defined with customized reconstructions following the aortic course and angioscopic views [1].

**Intramural hematoma**

Intramural hematoma is most probably caused by a rupture of the vasa vasorum leading to hematoma formation within the media. On non-contrast enhanced CT the blood in the media can be discerned as a bright rim (figure 23).

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**Figure 23**

Unenhanced axial CT image in patient with acute aortic syndrome, a bright rim can be discerned indicating presence of intramural hematoma (arrowhead)

**Figure 24**

a: coronal MPR of CTA demonstrating penetrating ulcer (arrowhead); b: sagittal MPR of same patient demonstrating dorsal extension of ulcer (arrowhead)
Penetrating ulcer
A third entity that is part of acute aortic syndrome is athero-sclerotic penetrating ulcer. In penetrating ulcer the internal elastic lamina is disrupted. In typical penetrating ulcers the hematoma is contained by the atherosclerotic changes of the intima (figure 24).

Aneurysms
Aneurysms of post-traumatic origin should be considered false aneurysms, and are usually the result of a chronic, contained rupture at the level of the aortic isthmus. True thoracic aortic aneurysms occur in up to 10% of elderly patients, and are most commonly atherosclerotic in etiology. In the evaluation of aneurysms accurate depiction of aortic caliber, morphology, relationship to aortic arch vessels and the presence of thrombus or ulceration is of importance in deciding whether and how to intervene (figures 25–27). Volume rendered imaging has become indispensable for the evaluation of endovascular stent placement, by demonstrating to advantage the spatial relationship between the aorta and major arch branches [1]. Major risk of true aneurysms is spontaneous rupture, and therefore treatment is advised in cases where aneurysm size is over 6 cm in diameter (figure 28). Treatment may consist of open surgical repair or endovascular repair (TEVAR). After TEVAR follow-up, CTA or MRA should be performed in order to demonstrate full exclusion of the aneurysm, absence of aneurysm growth and absence of endoleaks (figures 29 and 30).

Figure 25
a: oblique sagittal MPR of aortic arch demonstrating false aneurysm at the level of the aortic isthmus (arrowhead) in patient that subdued a deceleration trauma 20 years earlier; b: coronal MPR of same patient demonstrating caudad extension of false aneurysm, with parietal thrombus (arrowhead); c: axial slice demonstrating ventral extension to advantage (arrowhead)

Figure 26
Para-sagittal MPR of CTA in patient with true aneurysm of the descending thoracic aorta (arrowhead)
**Figure 27**
a: 3D-RA; cinefluoroscopic image (AP-projection) of aneurysm of descending thoracic aorta; b: 3D-RA; default reconstruction in same patient; c: 3D-RA; volume-rendered image with cut-plane chosen through the longitudinal axis of the lumen, yielding angioscopic view

**Figure 28**
a: sagittal oblique MPR of CTA demonstrating rupture (contrast extravasation; arrow) of an aneurysm of the descending thoracic aorta; b: coronal MPR in the same patient (arrow indicates contrast extravasation)

**Figure 29**
a: axial CT slice of non-enhanced (dual source) CT in patient after endovascular aneurysm repair; b: axial CT slice of contrast-enhanced (dual source) CT in patient after endovascular aneurysm repair; c: calculated virtual native image obtained from the image shown in b; note somewhat blurred appearance
Conclusions

Three-dimensional vascular imaging techniques offer a significant advantage over traditional imaging techniques. Using these techniques, anatomical dissection can be performed in vivo, thus helping in identifying disease to advantage, and helping in preoperative planning of surgical and endovascular procedures. Technical developments are rapidly evolving, and in the near future even more sophisticated imaging systems will emerge.

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References


