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Contemporary Imaging Findings in Aortic Arch Surgery

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Abstract
Purpose of Review The purpose of this manuscript is to review the surgical techniques of aortic arch repair, imaging techniques for evaluating the pre- and post-operative aortic arch, and both normal and abnormal post-operative imaging appearances.
Recent Findings Aortic arch repair is a technically challenging and rapidly evolving procedure, utilizing a variety of surgical methods that result in variable imaging appearances. Imaging plays an important role in the diagnosis of aortic arch abnormalities, as well as diagnosis of abnormalities in the adjacent ascending and descending aorta. Imaging also plays a key role in post-operative evaluation and surveillance.
Summary Familiarity with aortic arch surgical procedures and their expected post-operative imaging appearances is crucial for the radiologist to identify the surgery performed, recognize surgical complications, and avoid imaging pitfalls that may be mistaken for complications.

Keywords Aortic arch repair · Hybrid aortic repair · Elephant trunk · Frozen elephant trunk

Introduction

Aortic arch repair is an evolving field, with relatively loose guidelines on indications and limited literature on imaging appearance and surgical techniques. Whether a partial or complete repair, aortic arch surgery is technically challenging, requiring interruption of cerebral and systemic circulation [1••]. Supportive techniques include cardiopulmonary bypass and hypothermic circulatory arrest with cerebral protective adjuncts; these are employed to safely manipulate the arch vessels [1••]. Imaging plays a key role in diagnosis and pre-operative planning for aortic arch disease, as well as post-operative surveillance. Furthermore, imaging is required if management of the adjacent aorta is planned. The purpose of this manuscript is to review the indications and surgical techniques for aortic arch surgery, imaging techniques for evaluation of the pre- and post-operative aortic arch, and potential operative complications and imaging pitfalls.

Indications for Intervention of the Aortic Arch

Surgical Intervention

Aneurysm is a common indication for aortic repair, defined as dilatation of the aorta greater than 50% beyond its normal diameter [1••]. Isolated aortic arch aneurysms are

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rare, accounting for approximately 10% of aortic disease [2••, 3]. Guidelines for aortic arch intervention are less well defined than those of other aortic segments [1••]; in addition, a relative paucity of data on aortic arch pathology, natural history, and post-operative outcomes has resulted in less stringent criteria for surgical intervention. Complete operative aortic arch replacement is indicated when the entire arch is aneurysmal (greater than 5.5 cm) or if rate of growth exceeds 0.5 cm/year [1••, 4].

Isolated aortic arch aneurysms are frequently asymptomatic and discovered incidentally [1••], or they may alternatively cause symptoms related to compression on other organs (chest pain, dysphagia, hoarseness, recurrent respiratory infections) [1••]. In these cases, symptomatology may supersede the standard measurement thresholds for intervention [2••]. However, aortic arch abnormalities commonly occur in conjunction with abnormalities in the adjacent segments of the aorta, and decisions on arch surgery are often dictated by disease in the contiguous aortic segment [2••]. In our practice, ascending aortic abnormalities may be the primary indication for surgery, but aortic arch replacement is also performed for concomitant arch disease. Additionally, descending aortic disease may be addressed by creating a landing zone for endovascular repair.

Acute aortic dissection and intramural hematoma are classified according to the origin and extent of aorta involved. The Stanford classification system typically divides aortic dissections into type A (involving the ascending aorta) and type B (not involving the ascending aorta) [2••]. Surgical nomenclature is evolving regarding aortic arch dissection being classified as type A, type B, or a separate classification. Type A aortic dissection is considered a surgical emergency [5]. Type B is typically initially managed medically, with potential subsequent non-emergent intervention. However, if the dissected aortic arch is aneurysmal or if there is extensive arch destruction, surgical replacement of the entire aortic arch is recommended [2••]. Other details such as location of the dissection, size of the dissected aorta, clinical complications, and patency of the false lumen should be reported to aid in surgical planning [5]. In our practice, aortic arch repair may be performed for chronic/residual dissection or growing aneurysm after type A dissection repair to redirect flow into the true lumen.

Endovascular Repair

Thoracic endovascular aortic repair (TEVAR), stent-graft placement has emerged as both an adjunct and alternative to traditional open surgical aortic repair, primarily in the straight or tubular portion of the descending thoracic aorta (DTA). It can avoid the morbidity of a thoracotomy for open repair, and may also reduce or avoid high-risk maneuvers such as circulatory arrest and aortic cross-clamping [2••]. Furthermore, total endovascular repair may be offered to patients who are poor candidates for traditional surgical repair [2••].

To define the landing zones for stent-graft placement, the thoracic aorta has been divided into five zones [1••, 6]. In the Criado classification system (Fig. 1), Zone 0 involves the entire ascending aorta and the origin of the innominate artery. Zone 1 spans the origin of the left common carotid artery. Zone 2 spans the origin of the left subclavian artery, and Zone 3 extends from the origin of the left subclavian artery to 2 cm down the DTA. Zone 4 extends from the end of Zone 3 through the DTA. This terminology is also used to describe the location of anastomoses in open or hybrid repair.

Some patients are not considered candidates for TEVAR. Endograft placement requires 1.5–2 cm of normal aorta both upstream and downstream of the aneurysm to be a platform for stent-graft placement [7], acting as a "landing zone" for hardware. In addition, these procedures require appropriate endovascular access, and extremely tortuous vessels or severe atherosclerosis may preclude endovascular approach [2••].

Hybrid aortic repair is a broad term encompassing procedures that combine endovascular stents and surgical grafts. A significant advantage of hybrid repair is the ability to combine a classically staged repair into a single procedure by addressing multi-segmental aortic disease with endograft placement [1••]. In addition, it can facilitate more downstream repair of the DTA or abdominal aorta if an additional procedure is planned [8]. Hybrid repair is classified into three types [9]. Type I is performed in isolated aortic arch aneurysm, with debranching of the arch vessels that are reconstructed on the native ascending aorta. Type II is performed with ascending aortic graft repair and stent-graft placement of the aortic arch; the arch vessels are

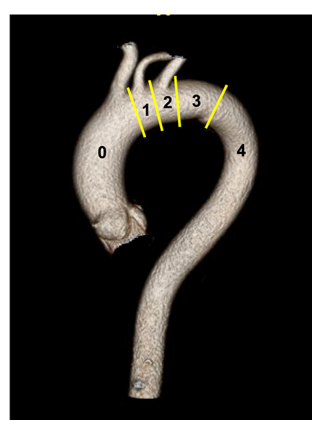

Fig. 1 Criado classification of thoracic aortic zones for endovascular repair

debranched and reconstructed on the ascending graft. Type III is performed in extensive thoracic disease, with graft repair of the ascending aorta and aortic arch; the graft creates a landing zone for endovascular DTA repair and may require staged repair. Hybrid procedures can be customized to each patient, adapting to the segment of aorta requiring repair, as well as creating appropriate landing zones for endograft placement.

Surgical Techniques and Imaging Appearance of Aortic Arch Repair

Hemiarch

Hemiarch (or partial arch) repair is a general term that describes replacement of the proximal aortic arch. It involves a variable degree of resection along the lesser curvature of the aortic arch; the greater curvature is left intact. Consensus guidelines recommend hemiarch repair in conjunction with ascending aortic repair when the aneurysm includes the proximal aortic arch. The beveled distal margin of the graft is anastomosed to the proximal aortic arch along the lesser curvature [1••, 10, 11]. The arch vessels (brachiocephalic, left common carotid, and left subclavian arteries) are controlled to maintain cerebral protection but remain in their native position [1••, 10], avoiding the need for debranching and reimplantation.

In more recent practice, hemiarch repair is frequently performed in conjunction with emergent ascending aortic repair for Type A dissection. In these cases, the focus is to direct as much flow to the true lumen as possible. In theory, this reduces re-operation rates by decreasing the rate of downstream and delayed aortic events [11]. This has driven the use of frozen elephant trunk (discussed below) in the setting of acute dissection to isolate true lumen flow.

On CT, the distal hemiarch anastomosis appears as an indentation along the undersurface of the aortic arch with a beveled margin with the native aorta. The arch vessels remain attached to the greater curvature of the native aortic arch (Fig. 2). 3D surface reformats may be helpful in identification of the distal anastomosis. The proximal anastomosis has a variable appearance and may be sewn to the native aortic root, a Valsalva graft, or to a prosthetic aortic valve (depending on what additional procedures have been performed). Felt pledgets may be used to reinforce the anastomosis, aiding in localization of the anastomosis on CT. In our practice, felt pledgets may be sandwiched on both sides of the anastomosis, buttressed on the outside of the suture line, or placed into the false lumen as a neomedia to promote flow into the true lumen.

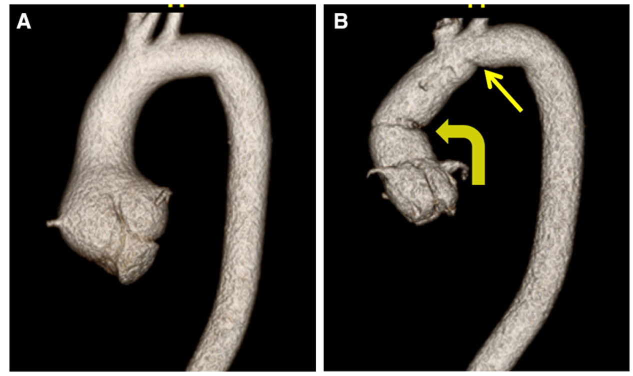

Fig. 2 Hemiarch replacement. **a** Pre-operative imaging demonstrates dilatation of the aortic root and ascending aorta. **b** Post-operative 3D surface reformat demonstrates changes related to hemiarch repair. The hemiarch is visualized as a beveled anastomosis (straight arrow) along the lesser curvature of the aortic arch. There is also an anastomosis between the hemiarch graft and a valve sparing aortic root repair (curved arrow)

Total Arch Repair

With extensive aortic arch aneurysm or dissection, a hemiarch repair is insufficient for the degree of aortic disease. Complete aortic arch repair is instead required to treat the mid and distal aortic arch. In all cases of total aortic arch repair, the arch vessels must be dissected from the native aorta and re-implanted to the new aortic graft. The following configurations can be used:

Total Arch with Island Patch

In the island patch repair, the arch vessels are removed *en bloc* from the aorta and attached to the graft as an "island" of native aortic tissue. Because the normal architecture of the arch vessels is preserved, the island patch technique resembles the normal appearance of the aortic arch on post-operative imaging.

The primary advantage of this technique is reducing surgical and circulatory arrest times [1••]. However, because it involves transferring a portion of diseased native aortic tissue, there is an increased risk of anastomotic pseudoaneurysm in the short-term post-operative periods, and patch aneurysm in the long-term post-operative periods [1••]. For this reason, the island patch repair is typically avoided in young patients, particularly those with connective tissue disease [3].

Four-Branched Arch Replacement

This method of arch reconstruction employs a pre-fabricated 4-branched graft. In addition to the three arch vessels, a fourth side branch is used for cardiopulmonary bypass [12]. The arch vessels are individually anastomosed to the graft branches. The fourth side branch is ligated at the completion of the surgery [1••]. Although this is associated with longer bypass times than the island patch repair, it allows for complete resection of the native aortic arch.

Total Arch with Y-Graft

The Y-graft was introduced by Spielvogel et al. [13] as an alternative approach to aortic arch reconstruction with the goals of decreasing cerebral ischemia, improving hemostasis, and allowing for complete removal of native aortic tissue [14]. In this method (also known as the Spielvogel technique), a branching graft from the aortic graft creates a platform for individual anastomosis of the arch vessels (Fig. 3) [1••]. The arch vessels are anastomosed and occluded individually in the reconstruction process, and during periods of individual vessel occlusion, the other branches can be perfused.

When possible, a left carotid–subclavian artery transposition or bypass is performed prior to sternotomy [4] to facilitate more proximal arch manipulation at the time of aortic surgery and improve surgical hemostasis (Fig. 4). A more proximal anastomosis of the aorta-to-graft (proximal to the left subclavian origin) avoids injury to the left recurrent laryngeal nerve and improves surgical hemostasis [1••, 3]. Alternatively, a fenestration through the graft or stent graft has also been employed to preserve flow to the left subclavian artery which would otherwise be covered [8]. In cases requiring a more proximal aortic repair, carotid–carotid artery bypass accompanies the left carotid–subclavian artery bypass [6].

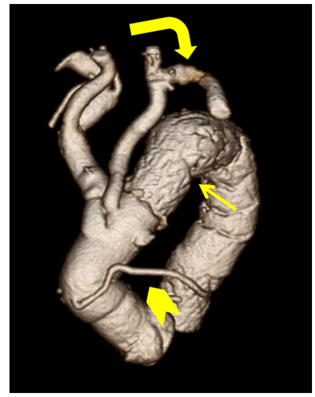

Fig. 4 Zone 2 repair with subclavian revascularization. 3D surface reformat demonstrates post-surgical changes from aortic arch replacement and frozen elephant trunk repair. A carotid–subclavian transposition (curved arrow) was performed, allowing for a more proximal placement of the stent graft (straight arrow). Incidentally, a saphenous vein graft is present (arrowhead)

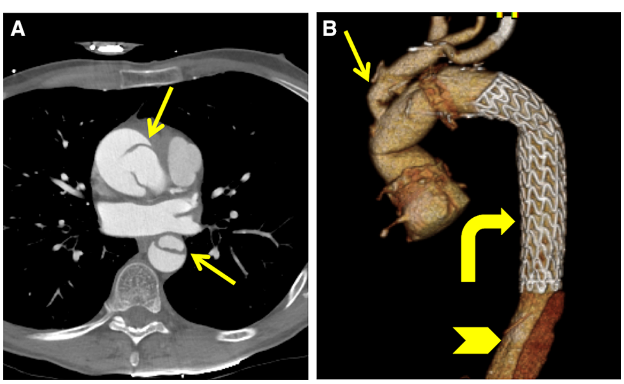

Fig. 3 Trifurcated Y-graft of the aortic arch with frozen elephant trunk repair. **a** Axial CT images from a gated CTA demonstrates an acute Stanford Type A dissection. There is a dissection flap with intimal defect in the ascending aorta and descending aorta (straight arrows). The dissection flap also involves the aortic arch (not included on the field of view). **b** Follow-up imaging after frozen elephant trunk repair. A branching tri-furcating Y-graft (straight arrow) has been anastomosed to the ascending aortic graft, supplying the right brachiocephalic, left common carotid, and left subclavian arteries. A stent graft has been placed in the true lumen of the descending aorta (curved arrow). Note the residual dissection in the downstream descending aorta (arrowhead)

Surgical Techniques and Imaging Appearance for Combined Aortic Arch and Descending Aortic Repair

Classic Elephant Trunk

The classic elephant trunk procedure was first described by Borst et al. [15] as a staged repair of extensive aortic disease—the ascending aorta and arch via sternotomy and the DTA via left thoracotomy [1••, 16••] (Fig. 5). In stage 1, the ascending aorta and arch are repaired and anastomosed to the distal arch with a free-floating portion of the graft (termed the elephant trunk) left suspended within the proximal DTA [1••]. In the setting of aortic dissection, the dissection flap is resected and fenestrated as far down into the DTA as possible to open the true lumen. On CTA, the free-floating elephant trunk appears as a flap-like structure, with contrast on both sides, mimicking a residual aortic dissection. Radiopaque markers may be placed along the elephant graft to facilitate stage 2. Careful correlation with surgical history is necessary for accurate identification of expected post-operative findings.

The classic open elephant trunk repair is associated with several inherent risks. In most cases, patients are allowed to recover between stages for a 4–8 weeks interval [1••]. During this period, patients remain at risk for dissection, pseudoaneurysm, or rupture of the native descending aorta; up to 25% of patients do not survive to the second stage [9]. In addition, the inherent risks associated with a second

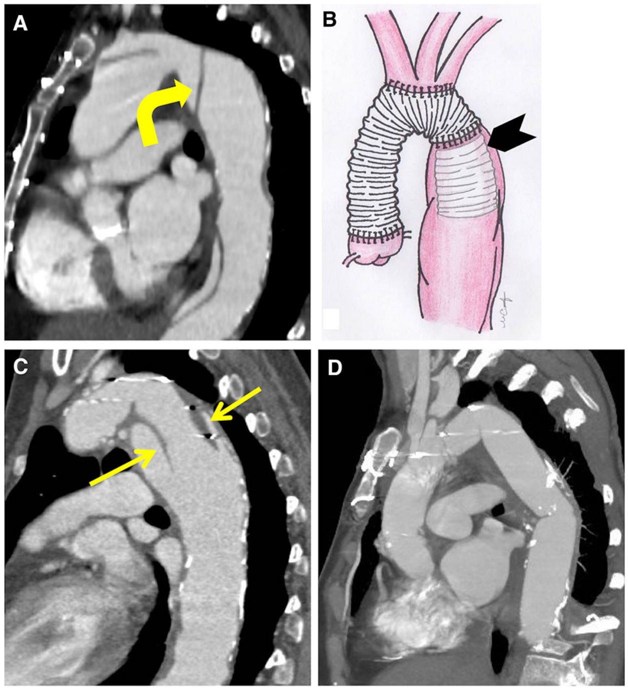

Fig. 5 Classic elephant trunk repair. **a** Initial pre-operative CTA images demonstrates a chronic dissection flap in the aortic arch and descending aorta (curved arrow). **b** Illustration for of the elephant trunk repair after stage I repair. Note the free-floating graft in the DTA (arrowhead). **c** Contrast-enhanced CTA images following Stage 1 repair of the ascending aorta and aortic arch. The free-floating elephant trunk graft is in the descending aorta (straight arrows), mimicking a dissection flap. **d** Post-operative MIP reformat images following stage 2 demonstrates completion of the descending thoracic aortic replacement. Illustration is reproduced from Fig. 10a in original publication: Green DB. Mimics of complications in the post-operative aorta on CT. *Radiology: Cardiothoracic Imaging* 2019;1(4):e190080. ©RSNA, 2019

surgical procedure have to be considered in patients with multiple comorbid conditions.

The elephant trunk then facilitates DTA repair during the second stage via either left thoracotomy or an endovascular approach [10]. The elephant trunk graft is retrieved and extended to replace the DTA. After completion of both stages of the elephant trunk procedure, the imaging appearance is identical to graft repair performed by any open method without evidence of prior elephant trunk.

Frozen Elephant Trunk

In 1996, the frozen elephant trunk repair was introduced as an alternative to the classic elephant trunk procedure [17]. This modification allows both aortic arch and proximal descending aortic repair to be performed in a single procedure, eliminating the risks of a staged procedure. From a median sternotomy approach, an endovascular stent graft is introduced into the distal aortic arch/DTA during circulatory arrest in an antegrade fashion [1••, 3], utilizing intravascular ultrasound to identify the true lumen in dissection. The proximal aspect of the stent is securely sutured at the anastomosis, similar to the technique used in a classic elephant trunk. However, the distal aspect of the stent graft can be anchored to the DTA, fully excluding the descending aortic aneurysm and repairing both the aortic arch and DTA in a single procedure (Fig. 3b) [18]. In the case of a dissection, placement of a stent graft into the DTA excludes the false lumen [4]. Another method is to place a soft surgical graft, followed by a stent graft in a stepwise fashion.

More recently, a modified frozen elephant trunk technique has been introduced—the Buffalo trunk repair [1••]. As part of this modification, the stent graft is placed inside a traditional surgical graft, both are delivered into the true lumen of the DTA simultaneously. By deploying the stent graft and soft graft at the same time, this repair is associated with shorter bypass and circulatory arrest times than a traditional frozen elephant trunk repair [4]. The post-operative imaging appearance of the frozen elephant trunk and buffalo trunk repairs are nearly indistinguishable. The key difference is that in the buffalo trunk repair, the anastomosis between the graft and the stent graft is reinforced with a felt strip along the outer surface of the surgical margin. On CTA, the felt ring creates a hyperdense demarcation of the anastomosis.

Imaging Techniques of Post-operative Aorta

Cross-sectional imaging of the thoracic aorta is indicated after aortic dissection or non-emergent repair of the ascending aorta. In the case of chronic type B dissection or repaired type A dissection with residual downstream dissection, the weakened aorta remains susceptible to ongoing dilatation. Current guidelines for imaging recommend follow-up imaging at 1, 3, 6, and 12 months after surgery, and following this, yearly monitoring for aortic enlargement [2••]. Guidelines also suggest follow-up with a single modality for better comparison (e.g., either or CT or MR, not alternating) [2••].

CT is the mainstay of post-operative evaluation of the aorta, due to its ready availability and high spatial resolution. In our practice, we routinely obtain a non-contrast phase on the first post-operative CT examination. Initial non-contrast images allow for reliable identification of hyperdense surgical material [16••], which can be difficult to differentiate from pseudoaneurysm or leak on post-contrast images. In addition, this allows for identification of hyperdense blood products and post-operative hematoma, which may also be obscured on post-contrast images [16••]. If available, dual-energy CT may be used to employ ultra-high pitch, low-dose technique or virtual non-contrast image reconstruction [16••]. In our practice, we obtain non-contrast images only on the first post-operative imaging study; subsequent examinations can be performed in the post-contrast phase only, provided no other surgical intervention has been performed to alter the baseline appearance of the surgical field.

After non-contrast images are obtained, CTA images should be performed with either ECG gating or ultra-high pitch technique to reduce artifact related to cardiac motion in the aortic root or the ascending aorta [1••, 16••]. Retrospective gating is favored, as some abnormalities may be seen only on certain phases of the cardiac cycle [19•]. In our practice, we routinely use retrospective gating with dose modulation for CTA evaluation of the aortic root and ascending aorta. Delayed venous phase images are obtained to assess for endoleaks after endovascular repair [16••] and late opacification of the false lumen in residual dissection. Other complications may be best seen on venous phase, including inflammatory fat stranding or rim enhancement related to infection. In our practice, post-processing techniques such as multiplanar reformats, maximum intensity reformats, and 3D volume rendering are typically performed.

MRA can also be used to evaluate the post-operative aorta. MRA should be performed using ECG gating, to minimize cardiac motion artifact. As major advantage, MRA uses no ionizing radiation, and can be used when iodinated intravenous contrast is contraindicated. MR may also better differentiate slow flow from true thrombus in the setting of excluded aneurysm or false lumens [10, 19•]. However, the spatial resolution of MRA is lower than that of CTA, and images may be degraded by metallic artifacts-related surgical material or stent grafts.

Post-Operative Imaging

Normal Post-Operative Appearance and Potential Pitfalls

In the immediate post-operative setting, complex fluid and gas in the surgical bed can be a normal finding. In addition, hemostatic material such as Gelfoam® or Surgicel® may appear as a heterogeneous gas and fluid collection. Mediastinal blood products may also be present in the peri-operative setting. Mild rim enhancement may be a normal finding, and not necessarily infectious in the immediate post-operative setting [19•].

Felt pledgets are used for re-inforcement of anastomotic suture lines. On CT, these are intrinsically dense, and can mimic a pseudoaneurysm [19•]. Correlation with non-contrast images and knowledge of typical locations is key for correct differentiation of surgical material from pseudoaneurysm (Fig. 6).

When cardiopulmonary bypass is employed, side-arm grafts are used to perfuse the systemic circulation after distal anastomosis is completed. Typically located on the ascending aorta, innominate artery, or axillary artery, these branches are divided and tied off near the aortic graft at the end of surgery. On post-operative imaging, these appear as small outpouchings of contrast, mimicking a pseudoaneurysm (Fig. 7). However, careful correlation with the surgical history and operative report can help identify these normal sites of aortic cannulation. In addition, these side-arm grafts are typically hyperdense and measure approximately 8 mm in size [16••].

Mild rim enhancement of mediastinal or pericardial fluid collections may be a normal finding in the immediate post-operative period, and cannot be reliably distinguished from low-grade infection [19•]. In these cases, evaluation with direct fluid aspiration or a tagged white-blood cell scan can distinguish infection from normal post-operative enhancement.

Post-Operative Complications

Dehiscence

As described above, consensus guidelines for post-surgical imaging surveillance is designed to evaluate for both early and late complications related to aortic repair. In the early period, complications of aortic surgery include anastomotic leak/dehiscence and pseudoaneurysm formation. Dehiscence is most common in the immediate post-operative period [19•] and is characterized by contrast material

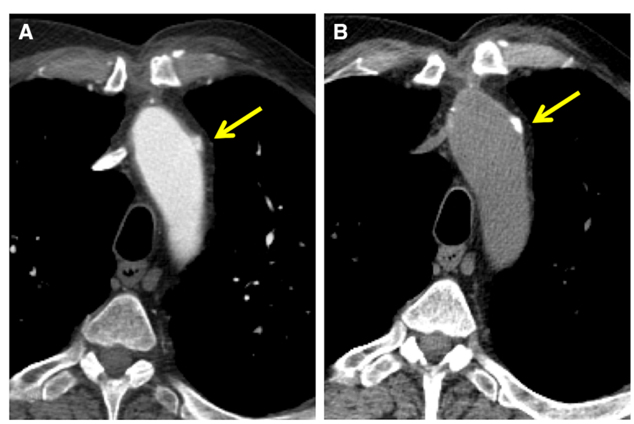

Fig. 6 Hyperdense felt pledgets. **a** Contrast-enhanced CTA image following aortic arch repair. A hyperdense focus along the lateral aortic arch (straight arrow) is suspicious for a pseudoaneurysm. **b** Non-contrast images demonstrate that this is intrinsically hyperdense and compatible with a surgical pledget

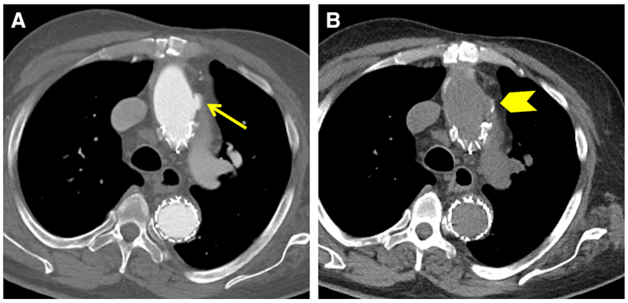

Fig. 7 Bypass cannulation site. **a** Post-contrast CTA images demonstrate a focal hyperdensity along the outer contour of the aortic arch (arrow) suggesting pseudoaneurysm. **b** Non-contrast images demonstrate intrinsic hyperdensity correlating with this area, compatible with a bypass cannulation site (arrowhead). This is a typical location for bypass cannulation, and should not be confused with a post-operative pseudoaneurysm

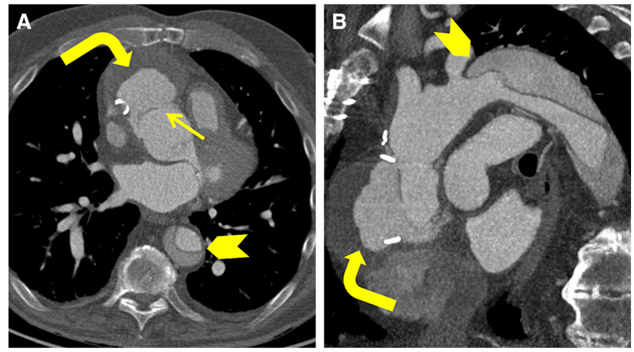

Fig. 8 Dehiscence following ascending aorta repair with acute type B aortic dissection. **a** Axial-gated CTA image demonstrates dehiscence along the ascending aorta anastomosis with a focal defect (straight arrow) and extraluminal contrast (curved arrow). An acute type B aortic dissection is present in the DTA (arrowhead). **b** Sagittal oblique MIP reformat demonstrates the collection of extraluminal contrast (curved arrow) and acute type B dissection arising distal to the left subclavian artery

external to the aortic lumen (Fig. 8). It most commonly occurs as a defect in the aorta, such as an anastomosis or site of bypass cannulation, resulting in contrast extravasation [19•].

Pseudoaneurysm

A pseudoaneurysm typically occurs at anastomotic suture lines, appearing as a saccular outpouching of contrast beyond the expected contours of the aorta on imaging (Fig. 9) [16••, 19•]. Pseudoaneurysms may also occur at the site of cardiopulmonary bypass cannulation [16••] or at sites of infection or abscess formation. On CT, pseudoaneurysms are characterized by a communication with the aortic lumen [19•], contained by a portion of the aorta or the surrounding tissues. When large, they can compress adjacent structures such as the airway or pulmonary artery. Post-operative pseudoaneurysms necessitate prompt re-intervention with open or endovascular repair.

Aneurysm, Dissection of the Native Aorta

Post-operative imaging can prove valuable in the evaluation of the remaining portions of the native aorta. When aortic repair is performed emergently for dissection, a residual chronic dissection may be left in the DTA. Post-operative imaging plays a key role in monitoring the chronic dissection, evaluating for changes in aortic size or propagation of the dissection flap.

Even after elective repair for aortic aneurysm, long-term follow-up on these patients may demonstrate delayed aneurysm dilatation of the remaining segments of the native aorta. Indications for re-intervention are the same as those described earlier, although the patient's surgical risk profile should be reassessed. These remaining portions of

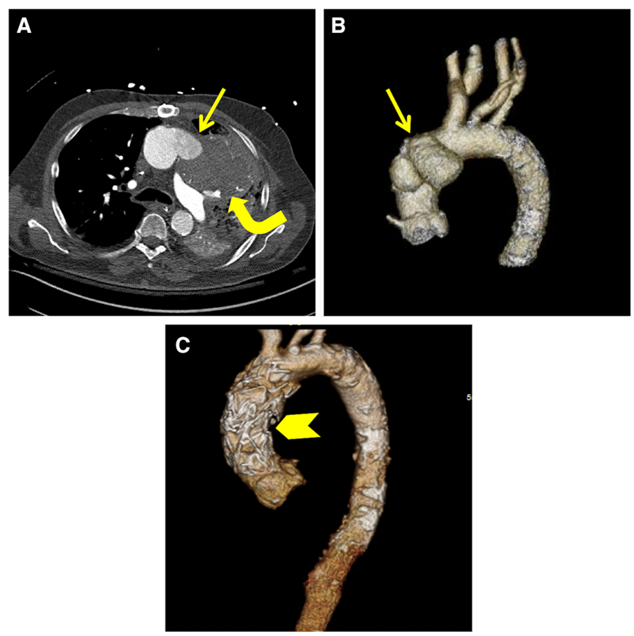

Fig. 9 Post-operative pseudoaneurysm. **a** Axial CTA image of a patient following coronary artery bypass grafting. Images demonstrate a large pseudoaneurysm along the ascending aorta (arrow), with an associated large mediastinal hematoma (curved arrow). **b** 3D surface reformat shows the bi-lobed shape of this pseudoaneurysm, located along the ascending aorta (arrows). **c** Due to multiple comorbid conditions, this patient was not considered a candidate for re-do sternotomy and open repair. 3D surface reformat after Zone 0 TEVAR demonstrates a new stent graft along the ascending aorta, upstream of the arch vessels (arrowhead)

native aorta may also undergo aortic dissection (particularly in patients with connective tissue disease), requiring more urgent intervention [16••].

Endoleak and Retrograde Flow

In the setting of a frozen elephant trunk or complete endovascular aortic repair, a stent graft is secured along an aneurysmal portion of the aorta. The stent graft is intended to exclude the diseased aorta and requires an adequate seal proximally and distally to prevent endoleak—flow from the aortic lumen into the excluded peri-graft space. Persistent flow outside of the stent graft is the most common complication after stent-graft deployment [20] and can lead to progressive aneurysm enlargement and potential rupture [16••].

Endoleaks are classified into 5 different types, based on the cause of abnormal blood flow [21]. Type I endoleaks occur from incomplete attachment at the proximal (IA) or distal site (IB) of the stent graft (Fig. 10). Type II endoleaks occurs from collateral flow into the aneurysm sac. In the thoracic aorta, type II endoleaks can occur from intercostal or bronchial collaterals; they can also occur from the left subclavian artery if carotid–subclavian bypass has been performed without occlusion of the subclavian origin. Type III endoleaks occur secondary to structural failure of the stent graft, and Type IV is due to graft porosity. Type I and type III endoleaks are seen on CTA with contrast outside of the endograft on arterial phase. Delayed images may be necessary or visualization of a type II endoleak, with slow enhancement of the false lumen or aneurysm sac from collateral vessels. Type V endoleaks are characterized by endotension, elevated pressure within the aneurysm sac [21, 22]. Type IA endoleaks do not occur in frozen elephant trunk repair, as the proximal portion of the stent is sewn to the anastomosis.

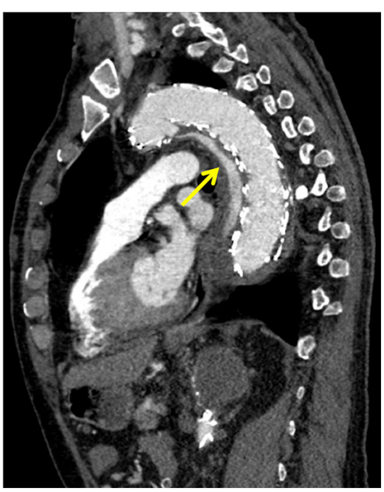

Fig. 10 Type IA endoleak after TEVAR. Sagittal oblique image demonstrates Zone 2 placement of an endovascular stent with contrast in the peri-graft space (straight arrow) secondary to a type IA endoleak

MRA using 4D flow analysis has recently been used for identification and evaluation of endoleaks. 4D flow has been shown to have a higher sensitivity than CTA for endoleak detection [23]. In the case of multiple types of endoleak, 4D flow is able to differentiate between multiple sources of endoleak [23], and can characterize velocity and volume of flow into the aneurysm sac [24].

Retrograde Type A dissection (RTAD), a new type A aortic dissection, is a potentially fatal occurrence after TEVAR involving the aortic arch or DTA. It can occur days, weeks, or months after an endovascular procedure [25]. Although incidence is only about 2.5% of cases, mortality rate may reach 37.1% [26]. Potential etiologies for RTAD include procedure-related aortic injury or device-related pressure on the weakened aortic wall [25]. RTAD is associated with a more proximal placement of a stent graft (in zones 0–2), oversizing of the stent graft [25, 27], and is more common when repair is performed for dissection rather than aneurysm or atherosclerosis [26]. When it occurs, RTAD requires ascending aortic and full arch repair.

Infection

Infection of graft material may occur at any point in the post-operative state. Initial findings typically include abnormal fluid or gas bubbles [16••], but can be difficult to differentiate from peri-operative inflammation in the immediate post-operative period. In these cases, delayed contrast images may be helpful to establish rim enhancement in the case of infected peri-graft fluid or abscess formation. In advanced cases, pseudoaneurysm or fistula may form [16••, 20].

Conclusions

Multiple surgical techniques are used in aortic arch repair, and these can have a variety of imaging appearances. Familiarity with these surgical techniques is crucial for the radiologist to understand the expected post-operative appearance, as well as identify potential complications and imaging pitfalls that may be encountered on post-operative evaluation.

Compliance with Ethical Guidelines

Conflict of interest Bang, Green, Reece, DaBreo, and Vargas declare no conflicts of interest.

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Papers of particular interest, published recently, have been highlighted as:

- • Important
- •• Very important

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