Preoperative planning for endovascular aortic arch repair

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Background: Endovascular repair of aortic arch pathology is an evolving treatment option for selected patients, particularly those at high or prohibitive risk for conventional open arch replacement. However, the complex three-dimensional anatomy of the aortic arch, high pulsatile flow, proximity of the supra-aortic vessels, and the need for durable proximal and distal sealing make these procedures technically demanding. Careful patient selection, high-quality imaging, and systematic preoperative planning are therefore essential determinants of procedural success.

Methods: This article presents a structured approach to preoperative planning for endovascular aortic arch repair. The planning process includes confirmation of guideline-based indications for intervention, operative risk assessment, selection between open, hybrid, and total endovascular strategies, detailed computed tomography angiography analysis, three-dimensional reconstruction, centerline-based measurements, assessment of landing zones, supra-aortic vessels, access vessels, cerebral collateral circulation, and device-specific anatomical requirements.

Results: Computed tomography angiography remains the principal imaging modality for procedural planning and should include thin-slice acquisition, appropriate contrast opacification, electrocardiogram (ECG)-gated assessment of the ascending aorta and arch, and scan coverage extending from the circle of Willis to the femoral arteries. Systematic image analysis should begin with axial source images before three-dimensional reconstruction, in order to identify thrombus, calcification, shaggy aorta, dissection, intramural hematoma, anatomical variants, and other features relevant to device implantation. Centerline and curved multiplanar reconstruction allow accurate measurements of vessel diameter, length, curvature, landing zones, and supra-aortic vessel orientation. These data guide the selection of debranching, scalloped, fenestrated, or branched endovascular strategies.

Conclusions: Successful endovascular aortic arch repair depends on meticulous preoperative planning, multidisciplinary decision-making, and strict anatomical feasibility assessment. Because current arch endovascular technologies remain anatomically restrictive and device-specific, they should be applied only in carefully selected patients after comprehensive imaging analysis and comparison with available surgical alternatives.

Keywords: Aortic arch; endovascular repair; preoperative planning

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Introduction

Endovascular treatment of aortic arch disease is gaining increasing popularity and represents a rapidly evolving field of modern aortic intervention. A growing number of technological solutions are now available, including both patient-specific custom-made devices and off-the-shelf systems.

However, these technologies remain associated with important limitations. These are mainly related to the complex three-dimensional (3D) anatomy of the aortic arch, the strong pulsatile blood flow in this segment, and the need to preserve uninterrupted perfusion to the supra-aortic vessels. Consequently, good outcomes—both immediate technical and clinical results as well as long-term durability—can only be achieved in a carefully selected group of patients. Patient selection, preoperative preparation, and procedural planning therefore play a particularly crucial role in endovascular aortic arch repair.

Preoperative planning

Preoperative planning can be divided into several essential stages:

(I) detailed diagnostic assessment;
(II) confirmation of the presence, extent, and morphology of the pathology requiring treatment;
(III) operative risk assessment and selection between open surgical and endovascular repair;
(IV) image analysis and 3D modelling based on the acquired imaging data;
(V) selection of the treatment strategy;
(VI) selection of the specific technological solution, including collaboration with the medical device industry, particularly when patient-specific custom-made devices are required.

All these stages should be performed within a dedicated multidisciplinary aortic team. Such a stepwise and systematic approach to planning may substantially improve clinical outcomes and reduce the risk of both early and late complications, including endoleaks, stroke, aortic dissection, and new stent graft-induced entry tears.

The aim of this article is to present a general approach to image analysis and preoperative planning for endovascular procedures involving the aortic arch, regardless of the specific device used. This includes total or partial aortic arch repair, branched systems, fenestrated devices, and scalloped stent grafts. Therefore, the description of planning and image analysis is intentionally general and does not address device-specific technical details, which vary substantially between available technologies.

Detailed diagnostic imaging

Computed tomography angiography (CTA) remains the principal imaging modality for the assessment of aortic disease. It should be performed using an appropriate scanner, preferably with more than 64 detector rows. Images should be acquired with a slice thickness of less than 1 mm. The scan range should include the circle of Willis and extend distally below the bifurcation of the femoral arteries (1).

The heart, the entire ascending aorta, and the aortic arch should be assessed using electrocardiogram (ECG)-gated acquisition to minimize motion artefacts caused by pulsatile movement of the aorta in this region. A three-phase computed tomography (CT) protocol should be performed. The first phase should be non-contrast. The second phase should be an arterial contrast-enhanced phase of the aorta. After contrast administration, homogeneous opacification of the entire aorta and its major branches should be obtained, with attenuation exceeding 250 Hounsfield units (HU). The third phase should be a delayed phase, which is particularly important in patients with aortic dissection, malperfusion syndrome, suspected rupture or bleeding, intramural hematoma, and in those with previous endovascular procedures (*Table 1*).

Ideally, CTA should not only serve for procedural planning but should also be suitable for intraoperative use, including fusion imaging in a hybrid operating room.

Recent advances in CT imaging relevant to endovascular aortic planning include dual-energy CT, dynamic or four-dimensional (4D) CTA, and, most recently, photon-counting detector CT, which provides improved spatial resolution and spectral information compared with conventional energy-integrating detector CT.

All patients should also undergo echocardiographic evaluation, including assessment of ventricular function and valvular function. This evaluation should include an assessment of chamber size, wall thickness, and Doppler analysis of transvalvular flow. Other structural cardiac abnormalities should also be excluded.

If cardiac CT suggests significant coronary artery stenosis, coronary angiography should be performed, followed by percutaneous coronary intervention (PCI) when clinically indicated.

Table 1 Recommended computed tomography angiography parameters for preoperative planning of an endovascular procedure

Parameter	Value
Aortic enhancement target	≥250 HU
Slice thickness	<1 mm reconstructed slices
Scanner	Preferably ≥64 detector rows
Scan initiation	Bolus tracking or test bolus preferred over fixed delay
Saline flush	Recommended
ECG gating	Recommended/important for root, ascending aorta and proximal arch
Contrast volume/rate	Individualized to scanner, patient size, kVp, coverage, and iodine concentration
Anatomical range	From the level of the circle of Willis to the level of femoral arteries

ECG, electrocardiogram; HU, Hounsfield units.

Initial CTA analysis and confirmation of indications

The initial analysis of CTA should confirm the presence of an aortic arch pathology that represents an indication for treatment. The indications for endovascular treatment of aortic arch disease do not fundamentally differ from those used for open surgical repair.

All indications for intervention should be established in accordance with current clinical practice guidelines and recommendations issued by relevant scientific societies (1-3). A detailed discussion of disease-specific thresholds and indications is beyond the scope of this article.

Endovascular procedures are currently performed more often electively, particularly in chronic pathologies such as degenerative aortic arch aneurysm, aneurysmal degeneration after chronic aortic dissections, pseudoaneurysms, penetrating aortic ulcers, large endoleaks, and similar conditions. Increasing numbers of reports also describe successful treatment of patients with acute aortic syndromes.

Additional imaging modalities that may support the assessment of indications and confirm or exclude the presence of relevant pathology include magnetic resonance imaging and intravascular ultrasound.

Selection between open surgical and endovascular repair

Virtually all scientific society recommendations concerning the treatment of the aortic arch support conventional open aortic arch replacement in patients with low or intermediate operative risk. Endovascular aortic arch repair is generally reserved for patients with very high operative risk or prohibitive operative risk (1-3). This applies only when the patient also fulfills the anatomical criteria required for endovascular repair, which are assessed primarily by CTA analysis.

Operative risk assessment may be performed using widely available risk scores, including EuroSCORE, the STS risk score, and the AATS Aortic Surgery Database Risk Calculator. Based on the presented operative risk and after appropriate counseling, each patient must provide informed consent for the proposed intervention.

Detailed CTA analysis for endovascular aortic arch repair

Detailed CTA analysis for planning endovascular aortic arch repair should include several stages.

The first step is the systematic review of the original axial images, frame by frame. At this stage, the operator should identify features that may be missed during later 3D reconstruction. These include aortic and branch-vessel wall thickness, inflammatory changes, mural thrombus, shaggy aorta, intramural hematoma, thrombosed or non-perfused false lumen, and soft atherosclerotic plaques. The CT window settings should be adjusted appropriately, with a suitable balance between window width and level, so that calcifications and contrast-filled vessels can be assessed simultaneously (*Figure 1*).

At this stage, it is also necessary to identify anatomical variants that may complicate, or occasionally preclude, the procedure. These include the origin of a dominant left vertebral artery directly from the aorta, arteria lusoria,

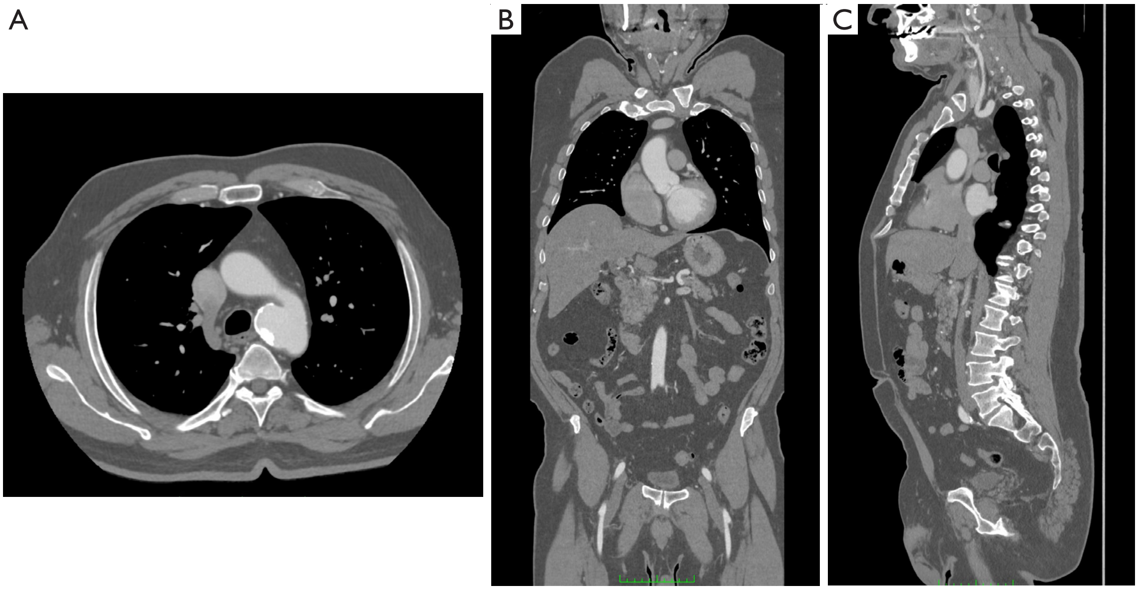

Figure 1 Axial (A), coronal (B), and sagittal (C) view of angio-CT. CT, computed tomography.

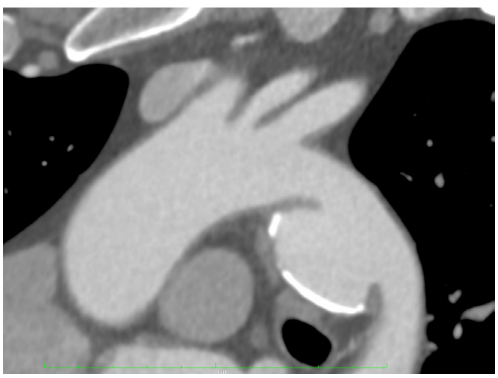

Figure 2 Curved multiplanar reconstruction.

the origin of the left common carotid artery from the brachiocephalic trunk, bovine arch anatomy, patent ductus arteriosus, coarctation of the aorta, and other relevant variants.

The next step is analysis of 3D reconstructions. Dedicated software is most commonly used for this purpose, frequently allowing semi-automatic analysis. Some modern platforms also incorporate artificial intelligence-based algorithms. Commonly used software includes EndoSize, 3mensio Vascular, and OsiriX. In addition, each CT scanner manufacturer provides dedicated workstation software that may also be used for endovascular planning.

The first stage of 3D analysis should include multiplanar reconstruction (MPR) (*Figure 2*). Curved 3D MPR is particularly useful for assessing the clock position of the ostia of supra-aortic vessels, especially when implantation of a triple-branched aortic arch prosthesis is being considered (4).

The software may automatically generate a centerline, defined as a line running through the center of the vessel along its long axis. Whenever automatic or semi-automatic software is used, the accuracy of the centerline must be checked and manually corrected when necessary. The centerline should begin at the left ventricular outflow tract and extend to the planned vascular access sites, most commonly the common femoral arteries, both common carotid arteries, and the left subclavian artery (*Figure 3*).

Only after accurate centerline generation is it possible to perform reliable assessment of vessel diameter or cross-sectional area, because measurements are then made perpendicular to the centerline. This avoids errors resulting from oblique measurement of vessel diameter.

At this stage, the diameters of the aorta and peripheral vessels should be assessed not only at the standard measurement levels defined in clinical practice, but also at device-specific points. These may include the diameter of the brachiocephalic trunk, common carotid arteries, and left subclavian artery.

Assessment of vascular access is an integral part of preoperative planning. The iliofemoral and common carotid

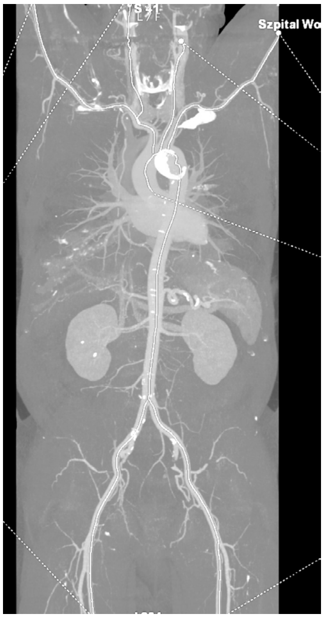

Figure 3 Centerlines in aorta and target vessels.

Figure 4 Stretched mode.

arteries should be analyzed for minimal luminal diameter, calcification, tortuosity, stenosis, previous surgical or endovascular intervention, and the presence of dissection or thrombus. The relationship between the required delivery-system profile and the access-vessel diameter must be carefully evaluated, which includes the minimum required diameter.

The centerline is also used to assess the length of individual aortic or vascular segments, the distance between anatomical structures, and the required length of stent graft components. For this purpose, the stretched-view mode is used, in which the centerline, aorta, and vessels are displayed as a straightened structure (*Figure 4*).

However, particular caution is required in curved segments such as the aortic arch and peripheral arteries. In these regions, stent graft length should be assessed with reference to the greater curvature, as this best reflects the actual length of the expanded stent graft. Accordingly, the measurement path should be adjusted to reflect the relevant curvature. The assessment of Ishimaru aortic zones and the distance between the origins of supra-aortic branches should also be performed along the greater curvature.

In contrast, the length of the landing zone, meaning the sealing zone, should be assessed along the lesser curvature. Evaluation of the lesser curvature and its angulation is important for estimating the risk of incomplete apposition, endoleak, and the bird-beak configuration.

Preoperative imaging should assess vertebral artery dominance, the origin and patency of the left vertebral artery, previous coronary artery bypass grafting using the left internal thoracic artery, and the need for surgical or endovascular LSA revascularization (5).

The next step may include 3D volume-rendering reconstruction to improve visualization of the aorta and facilitate further planning. At this stage, the type and angulation of the aortic arch can be assessed in detail. Among the three main aortic arch types, type III—the so-called gothic arch—is the most unfavorable anatomical configuration (*Figure 5*).

Selection of treatment strategy

Once the type and extent of the pathology have been defined and the preliminary anatomical CTA analysis has been completed, the treatment strategy and the appropriate type of intervention can be selected.

Several strategies are available. These include extra-anatomical cervical debranching or intrathoracic debranching, followed by overstenting of selected supra-aortic branches. Another option is the use of scalloped or fenestrated stent grafts. These may be custom-made,

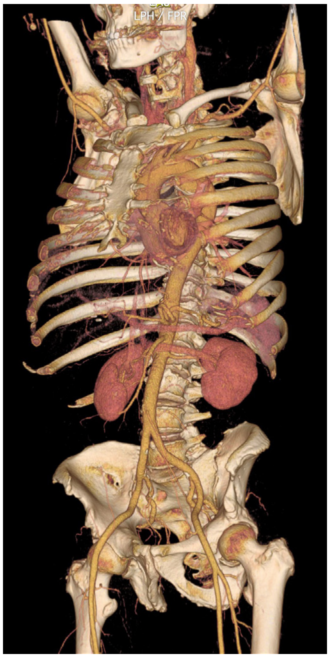

Figure 5 Volume rendering.

physician-modified on the back table, or fenestrated *in vitro*.

A third strategy involves branched devices with one, two, or three branches. In these systems, additional debranching may also be required, particularly when single- or double-branched devices are used. Single-branched systems may be available as off-the-shelf devices, whereas most other configurations are custom-made based on detailed CTA analysis.

Device-specific measurements and final planning

After the treatment strategy and device type have been selected, device-specific measurements must be performed.

Most commonly, the length of the ascending aorta containing the proximal landing zone is assessed. This is measured from the sinotubular junction to the proximal edge of the brachiocephalic artery, along both the lesser and greater curvatures. At these levels, the aortic diameter must also be assessed. In some patients with previous ascending aortic replacement, the proximal landing zone is located within a surgical graft; in such cases, the graft length and diameter must also be measured.

The criteria required for an adequate healthy landing zone are presented in *Table 2*.

For branched devices, rotation, mutual distance, and clock position of the supra-aortic target vessels must be assessed. The brachiocephalic trunk requires detailed evaluation, including its diameter and length. Similarly, the diameter of the carotid arteries and the left subclavian artery should be assessed. In the case of the left subclavian artery, the distance between the origin of the left vertebral artery and the aortic origin of the left subclavian artery must be measured in order to avoid inadvertent coverage of the vertebral artery.

As part of preoperative preparation for endovascular aortic arch repair, the completeness of the circle of Willis should always be assessed, particularly the A1 and P1 segments and the communicating arteries. The anatomical variant associated with the highest risk of neurological complications is absence or hypoplasia of the anterior communicating artery combined with absence or hypoplasia of both posterior communicating arteries.

Neurological risk assessment should include not only evaluation of the circle of Willis, but also assessment of the embolic potential of the aortic arch and supra-aortic vessels. Severe atheroma, mural thrombus, shaggy aorta, heavy calcification, and extensive manipulation within the arch may increase the risk of cerebral embolization.

Most systems designed for endovascular aortic arch repair have substantial anatomical limitations. Therefore, only approximately 50% of patients fulfil the anatomical criteria required for implantation of these highly complex devices. CT image analysis is also performed by the device manufacturer in order to design and produce a patient-specific system.

At the end of the planning process, it is possible to simulate the optimal angulation of the angiographic C-arm for intraoperative aortography. This allows imaging to be performed perpendicular to the implantation site of a given system component and may reduce both contrast volume and radiation exposure.

Endovascular treatment of aortic arch disease is a technically demanding procedure. It is also associated with a substantial risk of early and late complications. The main weaknesses of these procedures remain neurological complications and endoleaks. Therefore, appropriate planning, careful selection of the treatment strategy, and selection of the optimal device for each individual patient are of critical importance.

Table 2 Criteria for a healthy landing zone
• It is non-aneurysmal and not involved by the pathology being treated
• It provides an adequate sealing length—most commonly ≥20 mm, although the required length depends on the specific device and pathology
• Its diameter is within the IFU of the selected stent graft
• It does not contain circumferential thrombus
• It does not contain significant calcification that could impair endograft apposition
• It is not affected by IMH
• It is not affected by dissection, particularly in the proximal sealing zone
• It does not contain a penetrating aortic ulcer or ulceration
• It is not markedly tapered, funnel-shaped, or severely angulated
• It allows complete stent-graft apposition without significant bird-beak configuration, gutter formation, migration, or type I endoleak

IFU, instructions for use; IMH, intramural hematoma.

Many anatomical limitations continue to restrict the broad application of endovascular therapy for aortic arch disease. Detailed and systematic CTA analysis of the aorta and its branches is essential for achieving good technical and clinical outcomes in this challenging field.

Conclusions

Preoperative planning is a fundamental determinant of success in endovascular aortic arch repair. It requires high-quality CTA acquisition, systematic image analysis, careful assessment of anatomical feasibility, and multidisciplinary decision-making by an experienced aortic team. Because currently available endovascular arch technologies remain anatomically restrictive and technically complex, they should be applied only in carefully selected patients after detailed evaluation of operative risk, anatomical suitability, and available treatment alternatives.

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Footnote

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