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Review

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CT scan as a tool to evaluate root reconstruction and aortic valve repair

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Abstract

Cardiac computed tomography (CT) is an important tool in the management of patients with aortic root and ascending aorta dilatation. It complements echocardiography by providing high-resolution, three-dimensional images that enhance the assessment of aortic anatomy and help to determine the optimal timing for surgical intervention. Beyond preoperative planning, CT also plays an important role in postoperative surveillance by enabling early detection of changes or complications. Accurate imaging is essential for successful surgical outcomes, particularly given the complex structure of the aortic root and its relationship with the base of the left ventricle. Advances in CT technology, including improvements in spatial and temporal resolution, now allow surgeons to obtain highly detailed, accurate images of the aortic root, which are critical for planning aortic valve-sparing procedures. These detailed images provide a clearer picture of the root's anatomy and structural components, thereby supporting more informed and precise surgical decision making. Intraoperative decision making based solely on surgical experience may always yield optimal results. This is because the aortic root is not under physiological stress during surgery, and outcomes may vary depending on the surgeon's level of experience. These factors can influence the success of the procedure. This review highlights the growing importance of cardiac CT in the preoperative planning of complex aortic root surgeries. By providing clear, detailed anatomical data, CT enables surgeons to develop more individualized surgical strategies, ultimately improving outcomes and supporting personalized care for patients with aortic root aneurysms.

Keywords: Aortic valve repair, valve-sparing aortic root replacement, reimplantation, computed tomography, bicuspid aortic valve, postoperative surveillance

INTRODUCTION

In recent years, the field of cardiovascular medicine has undergone a paradigm shift, largely driven by significant advancements in medical imaging technologies[1]. Among these, computed tomography (CT) has emerged as a key non-invasive modality, providing high-resolution, three-dimensional views of the heart and its surrounding structures. Although CT cannot replace echocardiography or magnetic resonance imaging (MRI), which provide dynamic analysis and detailed information on the severity of valvular pathology, it offers superior spatial resolution, broader availability, operator independence, and high reproducibility. Consequently, cardiac CT, particularly when used with specialized acquisitions or reconstructions, has become a vital component in preoperative planning, postoperative assessment, and long-term surveillance of various heart conditions, including those requiring aortic root reconstruction and aortic valve repair[2].

Aortic root reconstruction and aortic valve repair are complex surgical procedures that require accurate pre-surgical evaluation to ensure optimal outcomes and effective long-term follow-up[3,4]. In this context, high-quality imaging plays a pivotal role in surgical planning, disease assessment, and procedural monitoring. Cardiac CT has demonstrated considerable value in improving patient care by providing detailed anatomical information about the aortic root, valve, and surrounding structures. This detailed visualization facilitates a comprehensive understanding of both anatomy and pathology, leading to improved surgical decision making. Additionally, postoperative CT imaging is crucial for the early detection of complications, thereby enabling timely intervention and enhancing long-term prognoses.

In this review, we present a step-by-step guide to the use of CT scans for the planning and evaluation of aortic root reconstruction and aortic valve repair, including technical considerations and postoperative applications.

CARDIAC CT SCAN: TECHINCAL CONSIDERATIONS

Technical requirements

To ensure high-quality and clinically useful imaging, a cardiac CT scan must meet several specific technical requirements. The quality of cardiac CT imaging is primarily determined by two factors: temporal resolution (TR) and spatial resolution (SR). Temporal resolution, which refers to the ability to capture images at precise points in time, is especially critical for cardiac imaging due to the heart's continuous motion. Imaging must therefore be synchronized with the heart's "resting phases" - typically mid-diastole (approximately 200 ms) and mid-systole (around 120 ms). To obtain a "stable" image during the cardiac cycle, a TR of less than 120 ms is generally required (and even shorter if the heart rate exceeds 75 bpm). Achieving such rapid image acquisition is possible through the following methods: (1) accelerated gantry rotation (although this is rarely feasible due to excessive G-force stress on components), (2) dual-source CT (which effectively halves the acquisition time), (3) wide-area detector (capable of capturing the entire heart in a single gantry rotation), or (4) multi-segment reconstruction (which combines data from multiple cardiac cycles but generally requires a higher radiation dose)[3]. Modern CT systems typically achieve a spatial resolution of approximately 0.5 mm slice thickness. While this level of resolution is not essential for evaluating the ascending aorta or aortic valve, it is particularly valuable for assessing coronary arteries and characterizing plaque morphology. Recent advances such as photon-counting CT have further improved spatial resolution[5], although such technology is currently not widely available.

Study protocols

Cardiac CT can be performed using two acquisition modes: prospective Electrocardiogram (ECG)-triggered sequential mode (step-and-shoot axial scanning) and retrospective ECG-gated helical mode. Although both modes offer comparable image resolution, the prospective mode typically results in a lower radiation dose. A third option, prospective high-pitch spiral acquisition (also known as "flash" mode), allows for further dose reduction but is only available on dual-source CT systems and is effective only at low heart rates (< 65 bpm)[6].

Imaging post-processing

Once the CT images are acquired, they are typically reconstructed using a 512 × 512 pixel matrix. Information along the Z-axis is then used to generate voxels, the three-dimensional volume elements that make up the CT dataset. The axial image dataset serves as the basis for all subsequent post-processing techniques, including: multiplanar reconstruction (MPR), curved MPR, maximum intensity projection (MIP), and 3D volume rendering. These methods are the cornerstone of cardiac CT interpretation. MPR is the most widely used technique; it provides a 2D view of the data along standard radiological planes (axial, coronal, sagittal), as well as any oblique orientation, enabling alignment with specific anatomical structures [Figures 1, 2, and 3]. Curved MPR allows a curved path to be defined through a 3D dataset, generating images perpendicular to that path. This is crucial for vessel assessment, as the reconstruction plane is aligned along the centerline of the vessel. MIP and volume rendering are less suitable for detailed measurements but are valuable for obtaining a general overview of cardiac and vascular anatomy[7].

STEP-BY-STEP CT SCAN ASSESSMENT FOR AORTIC ROOT RECONSTRUCTION AND VALVE REPAIR SURGERY

Here, we propose a stepwise approach to preoperative CT scan evaluation for aortic root and valve reconstruction surgery [Figure 4].

Supra-coronary ascending aorta, sino-tubular junction and aortic root

The indications for aortic valve regurgitation (AR) and ascending aorta aneurysms have been recently updated by major cardiological and cardiothoracic surgery societies[8-11]. Surgical intervention on the aortic valve, as indicated by the severity of AR, is determined primarily through echocardiographic assessment and clinical presentation. Historically, the principal criterion for surgical indication in aneurysm cases has been the maximum aortic diameter, with cardiac CT scans considered the gold standard for evaluating aortic dimensions. According to guidelines from the European Association for Cardio-Thoracic Surgery (EACTS) and the Society of Thoracic Surgeons (STS), measurements should be taken perpendicular to the aortic long axis at specific anatomical segments. Typically, eight measurements are obtained along the thoracic aorta, including outer-to-outer wall diameters. In addition to diameter, ascending aorta length has recently emerged as an important risk factor for aortic dissection and may further support surgical indications. This length is measured from the virtual basal ring (VBR) to the origin of the innominate artery using a dedicated curved multiplanar reconstruction (C-MPR). Once both diameter and length are assessed, the aneurysm phenotype, either root phenotype or ascending phenotype, can be determined. This distinction has major clinical implications, as the surgical threshold is lower for root phenotype in patients with a bicuspid aortic valve (BAV), with intervention recommended at 50 mm rather than 52/55 mm [Figure 5].

Next, the sino-tubular junction (STJ) should be evaluated. The typical STJ diameter is 16.8 ± 2.6 mm/m^2[10], but more importantly, the ratio between the STJ and VBR diameter is normally 1:1.3. Disruption of this relationship, referred to as "loss" of the STJ, can cause tethering of the aortic valve leaflets, leading to central jet regurgitation. This is particularly relevant in cases of ascending aortic aneurysms without dilation of the root or VBR, but with central AR.

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Figure 1. Multiplanar reconstruction (MPR) of a cardiac CT scan. From left to right: coronal, axial, and sagittal cuts. Beyond the standard planes, each can be rotated to produce oblique or double-oblique views. CT: Computed tomography.

Figure 2. Maximum intensity projection (MIP). This reconstruction technique displays the 3D structure by combining multiple CT slices. CT: Computed tomography.

Although the aorta is typically circular in cross-section, the complex shape of the aortic root requires specialized evaluation. Mori *et al*. identified three distinct root diameters[12]: bisecting, off-center left, and off-center right, with the latter generally being the largest. On average, the widest sinus-to-sinus measurement is approximately 3 mm greater than the center-to-center measurement. Therefore, accurate evaluation of the aortic root necessitates a dedicated MPR reconstruction to determine the true maximum diameter[12,13]. In the case of aortic root dilation, surgical replacement or reconstruction is recommended. Notably, a root diameter exceeding 45 mm should be considered an indication for surgical intervention, particularly when other primary indications, such as aortic valve pathology or a supra-coronary aortic aneurysm, are also present[8].

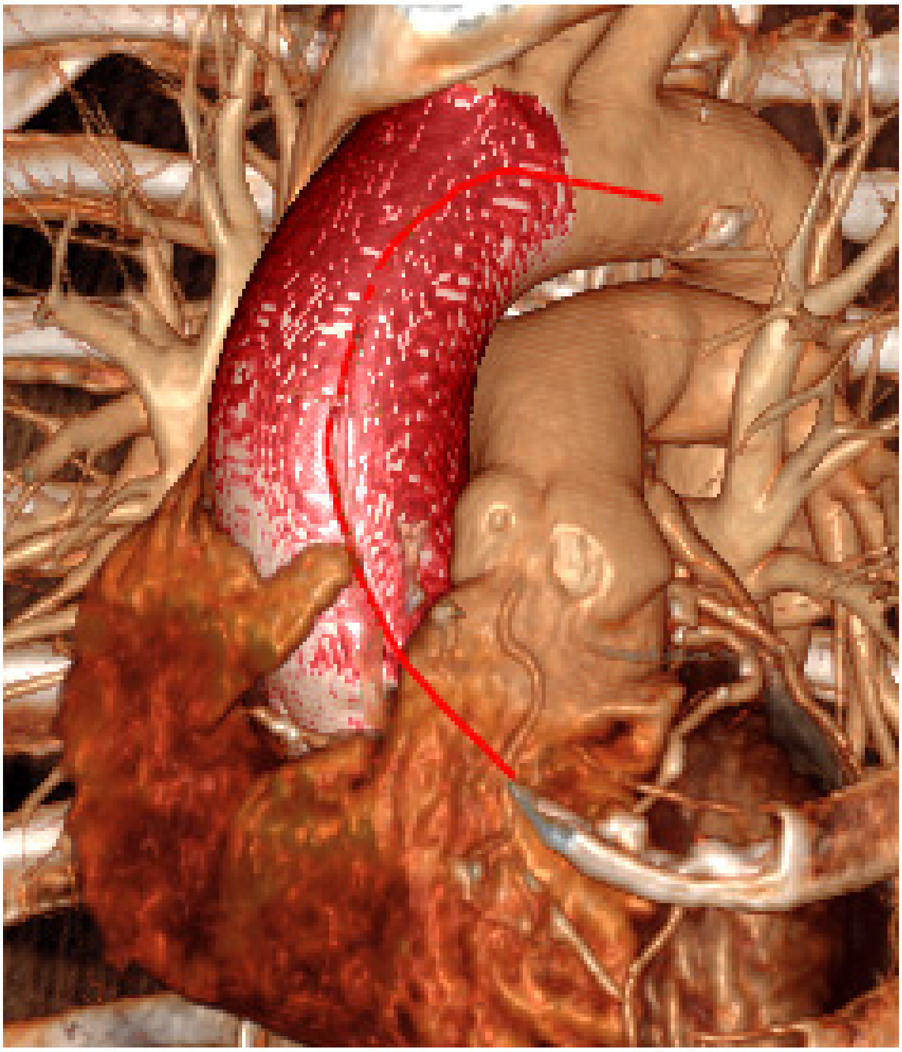

Figure 3. 3D volume rendering of the thoracic aorta. The volume of interest (VOI) is highlighted in red, along with the aorta centerline, which enables curved MPR reconstructions for vessel analysis. MPR: Multiplanar reconstruction.

Aortic annulus

Following the evaluation of the ascending aorta and aortic root, the next step is to assess the aortic annulus. The annulus is often referred to as the “functional aortic annulus”[14] due to its complex three-dimensional structure and multiple anatomical components: the crown-like leaflet attachments (also known as the surgical annulus or ventricular-aortic junction), the interleaflet triangles, and the VBR. In the context of CT imaging, the aortic annulus corresponds to the VBR - a virtual, coplanar contour connecting the nadirs of the three aortic valve leaflets. When properly visualized using dedicated oblique MPR or semi-automated reconstruction, the VBR typically appears elliptical, characterized by a major and minor diameter. Therefore, annular sizing is generally based on diameters derived from either area or perimeter measurements[15]. The dimensions of the VBR are critically important for determining the appropriate surgical approach. In cases of an enlarged annulus (> 25 mm), annuloplasty is required during isolated valve repair. When root reconstruction is performed, either reimplantation or remodeling combined with annuloplasty is recommended. The annulus shape must also be considered. As previously mentioned, tricuspid aortic valves typically exhibit an elliptical VBR, while BAVs with two sinuses often have a circular VBR, and three-sinus BAVs present an intermediate phenotype. During annuloplasty, the annulus is

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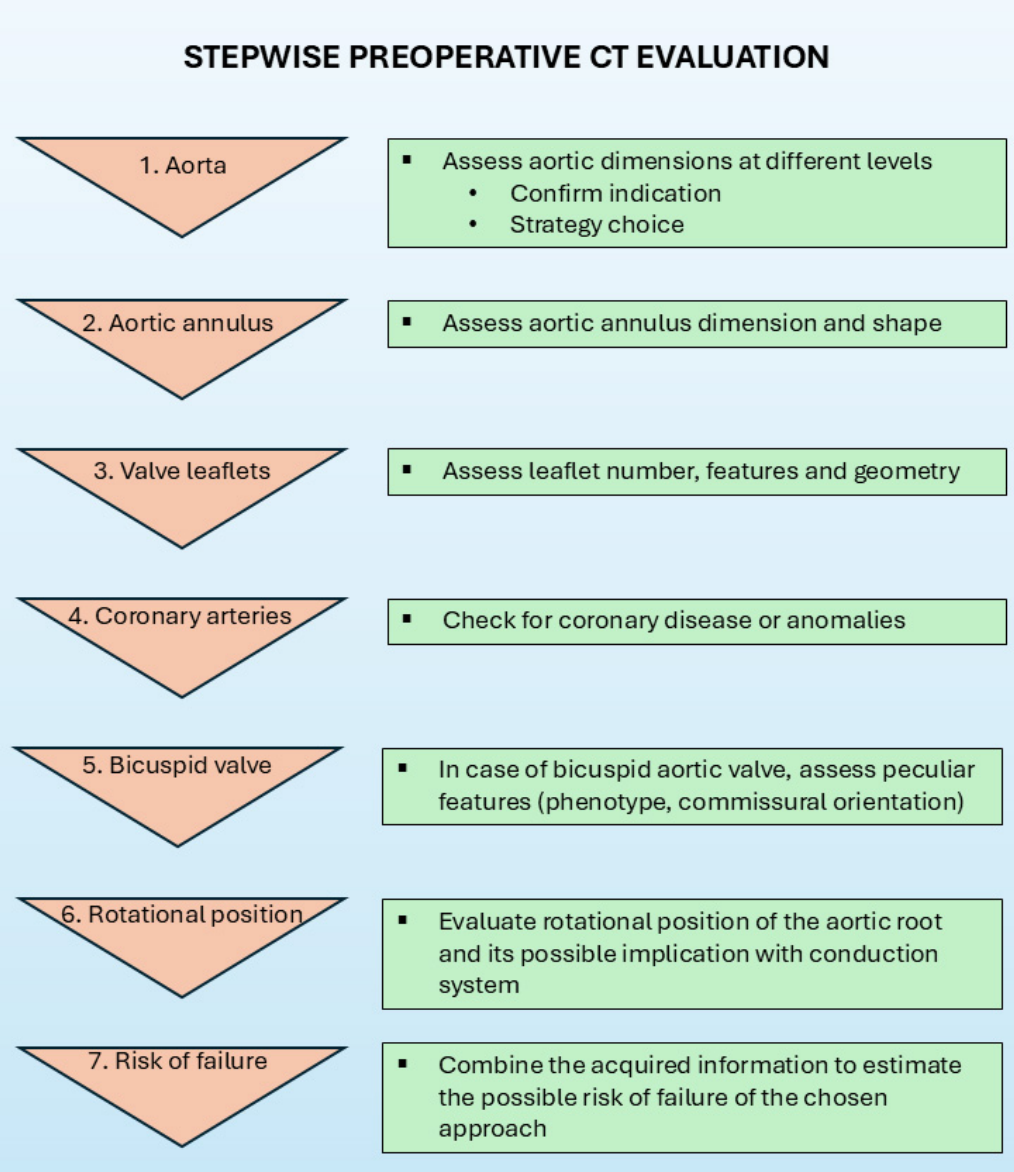

Figure 4. Flowchart outlining the step-by-step CT scan evaluation prior to aortic root and valve reconstructive surgery. CT: Computed tomography.

invariably reshaped into a circular configuration. This can lead to leaflet prolapse or deformation, particularly when the native annulus is highly elliptic[16]. Accurate measurement of annular dimensions is also essential for anticipating the appropriate size of the external annuloplasty ring if such a procedure is performed[17,18] [Figures 6 and 7].

Valve leaflets

Once all relevant diameters have been assessed, evaluation of the aortic valve leaflets should follow. The first step is to determine the number of leaflets and assess their macroscopic morphology. A recent consensus paper by the EACTS[19] has revised the historical classification[20]. According to this new classification, BAV, the most common congenital cardiac malformation, can be categorized into three phenotypes: 2-sinus BAV, fused BAV, and forme fruste. A detailed discussion on BAV assessment is provided in the following section.

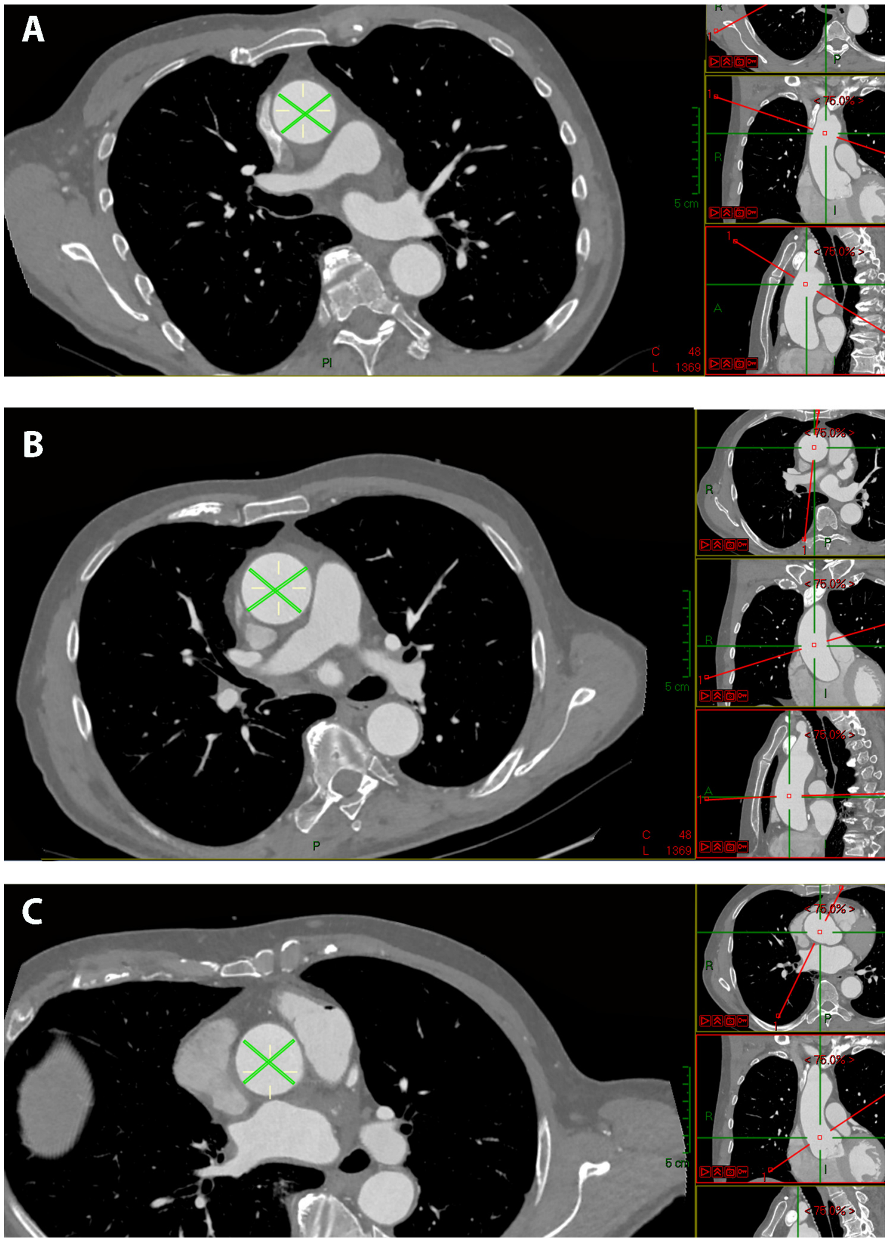

Figure 5. From bottom to top: three anatomical levels used for diameter measurement - sino-tubular junction (C), mid-ascending aorta (B), and origin of the brachiocephalic artery (A). The larger images on the left show the double-oblique planes used to measure diameters perpendicular to the aortic axis. The smaller images on the right illustrate the plane's orientation relative to the three main MPR axes (axial, coronal, sagittal). MPR: Multiplanar reconstruction.

In general, leaflet morphology can be easily assessed using a dedicated double-oblique MPR aligned parallel to the VBR. This view also enables the identification and quantification of leaflet calcification. The presence of significant calcific deposits, extensive fibrosis, or leaflet retraction is associated with a higher risk of valve repair failure. When such features are present, valve repair should be reconsidered in favor of prosthetic replacement[21].

Quantitative analysis of the leaflets can then be performed. It is important to note that CT-derived measurements in adults, while similar to intraoperative values, may differ slightly. These discrepancies are

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Figure 6. Double-oblique MPR image demonstrating correct alignment with the virtual basal ring (VBR), allowing for the measurement of VBR diameters (green), perimeter, and area (red). MPR: Multiplanar reconstruction.

likely due to the non-pressurized state of the aorta during CT assessment and the potential for leaflet distortion during image acquisition.

Two key parameters used to assess leaflet dimensions are geometric height (gH) and free margin length (FML). Geometric height is measured along the leaflet's midline, from the nadir to the free margin. A gH value less than 80% of the normal range indicates leaflet retraction.

In a normal trileaflet valve, this corresponds to a gH of less than 16 mm, while in a non-fused leaflet of a BAV, the threshold is less than 19 mm. As mentioned earlier, when aortic regurgitation is mainly caused by leaflet retraction, valve repair tends to yield less durable outcomes compared to regurgitation due to leaflet prolapse)[22]. FML is the distance between the commissures along the leaflet's edge. Comparing gH and FML guides the decision-making process for leaflet plication[10].

Leaflet coaptation is assessed using two additional measurements: effective height (eH) and coaptation length (cL). Effective height is the vertical distance from the VBR plane to the upper edge of leaflet coaptation. In normal valves, eH ranges from 8-10 mm, typically corresponding to 45% of the leaflet's gH[23]. A reduced eH may indicate leaflet prolapse, which requires correction. Coaptation length refers to the extent of leaflet overlap during coaptation. In adults, the mean cL is 3-5 mm. A light lateral increase in coaptation length is considered normal; thus, for accurate comparison with normative values, measurements should be taken at the central coaptation point using the bisecting center plane. Achieving an eH > 9 mm and a cL value > 5 mm correlates with a more durable valve repair[24]. Therefore, preoperative evaluation of leaflet geometry can help predict the feasibility of valve repair feasibility and/or the potential need for leaflet plication [Figures 8 and 9].

Coronary arteries

Coronary artery evaluation is essential in many patients prior to valvular surgery[10]. Coronary CT angiography has recently emerged as a valid non-invasive alternative[25]. Accordingly, in our patient cohort, performing a cardiac/coronary CT scan serves a dual purpose. In addition to assessing coronary stenosis

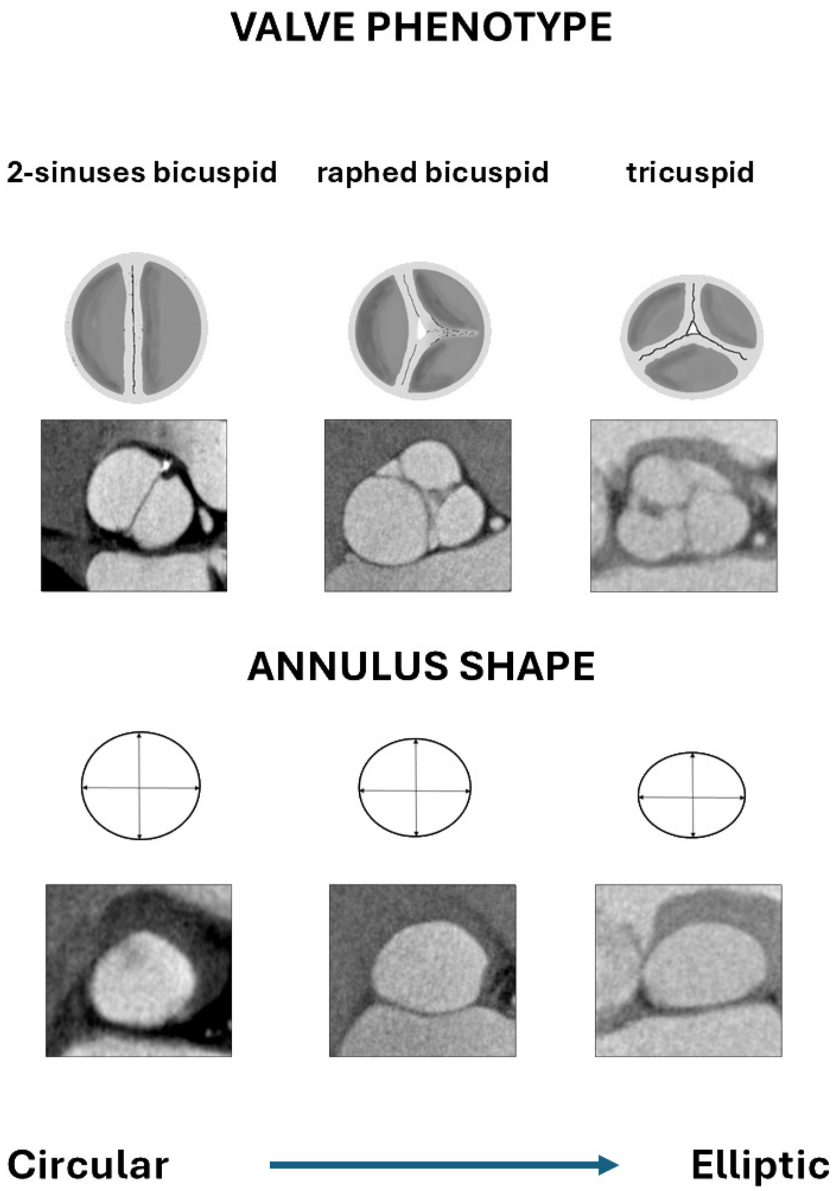

Figure 7. Diagram showing variability in annular shape based on valve phenotype.

and determining the necessity for revascularization, it is crucial to rule out coronary artery anomalies before performing aortic valve repair or aortic root reconstruction. This is due to the risk of injuring anomalously coursing coronary arteries during deep root dissection. Another important aspect to evaluate is the height of the coronary ostia. This is particularly important when performing an aortic valve repair with the implantation of an external annuloplasty ring, as very low coronary ostia can become compressed once the ring is tied. While it is not possible to define a definitive safe ostial height, being aware of this potential complication is strongly recommended [Figure 10].

Specific scenarios: BAV

BAV is the most common cardiac malformation and is often associated with various forms of aortopathy[18], with an even higher prevalence observed in populations undergoing aortic repair[17].

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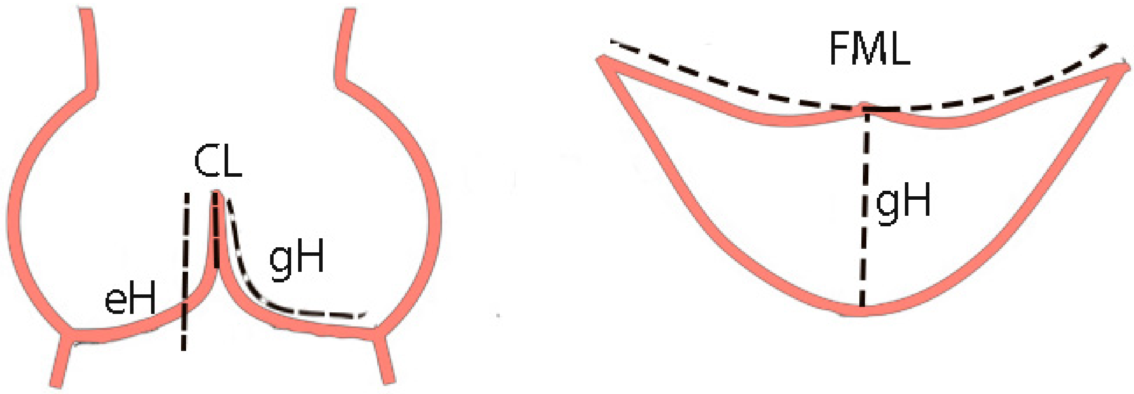

Figure 8. Schematic representation of leaflet features: eH (effective height), cL (coaptation length), gH (geometric height), and FML (free margin length).

Figure 9. CT image slice showing leaflet coaptation during mid-diastole. This enables measurement of geometric height (gH, yellow) and coaptation length (cL, red). For accurate assessments, these measurements must be taken in the plane passing through the nodules of Arantius, where gH is at its maximum and cL at its minimum. CT: Computed tomography.

For this reason, dedicated CT imaging is mandatory in patients with BAV. As noted above, the coexistence of aortic aneurysms is common, and the aneurysm phenotype can influence surgical decision making by lowering the threshold for intervention.

When planning BAV repair, it is crucial to determine the valve phenotype[18] and, consequently, its symmetry. Assessment using double-oblique MPR, aligned with VBR and extending from the VBR to the STJ during diastole, enables evaluation of the commissural orientation (CO) of the BAV, which typically varies from 120° to 180°. Preoperative identification of CO and valve symmetry helps the surgeon determine the feasibility of repair or the need for aortic root reconstruction to restore valve symmetry[26] [Figure 11]. It is widely accepted that BAV asymmetry is correlated with a higher risk of repair failure. In cases of fused BAV, the height of the commissures (or the interleaflet triangle height) can also aid in deciding whether to preserve the native configuration or convert the valve to a symmetric two-sinus BAV.

Whole root features: rotational position

Once the evaluation of individual valve and root components is accomplished, few additional insights can be obtained from cardiac CT imaging. The aortic root, when considered as a whole, can present varying degrees of axial rotation. These variations are associated with differences in the supporting tissue

Figure 10. 3D rendering of an anomalous circumflex artery originating from the right sinus and crossing the non-coronary sinus. Although this anomaly does not require correction in itself, it poses a significant risk of coronary injury during root dissection.

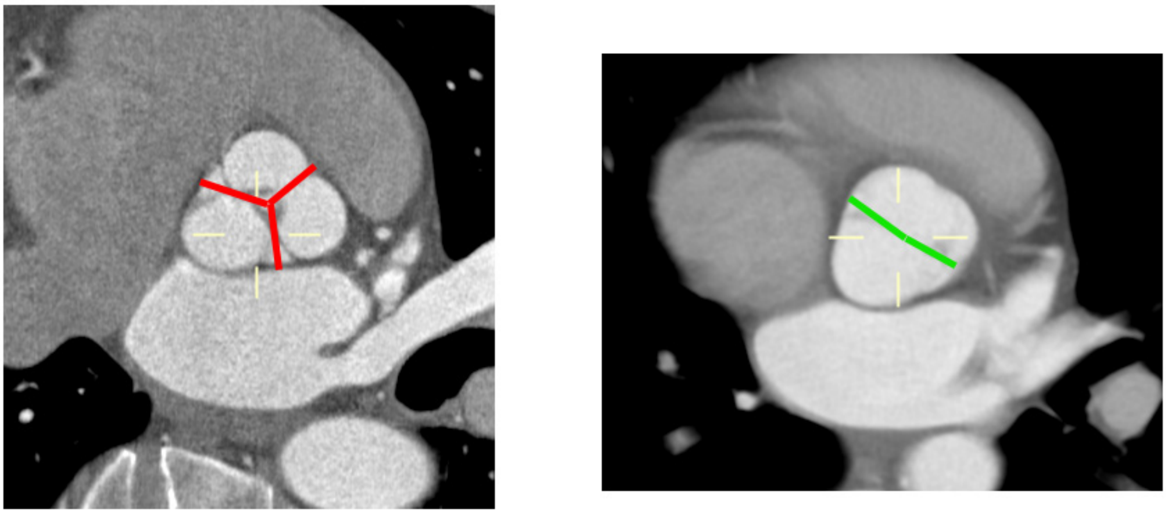

Figure 11. Left: a fused BAV phenotype with commissural orientation of approximately 120° (red lines). Right: a non-fused, two-sinus BAV with commissural orientation of approximately 180° (green lines)[26]. BAV: Bicuspid aortic valve.

composition of the aortic root (fibrous *vs.* muscular structures). The standard reference for rotational position is based on the CT view from the left ventricular, which is opposite to the surgeon's view from above. In this radiological perspective, clockwise rotation positions the right coronary sinus more anteriorly, away from the right atrium, while counterclockwise rotation brings it closer to the atrium. For quantitative assessment, the rotational angle can be measured by comparing the center of the non-coronary sinus to the right fibrous trigone. In normal adults, the mean angle is +16°, with a range from -32° to +45°. Clockwise rotation is associated with increased fibrous support, resulting in a wider and deeper inferoseptal recess, which is part of the central fibrous body[27]. Additionally, this rotation reduces the myocardial tissue at the base of the left coronary sinus while increasing it at the base of the right coronary sinus. The opposite changes occur with counterclockwise rotation. Interestingly, in children and young adults with genetic aortopathy, a clockwise-rotated root correlates with progressive dilation of both the aortic root and the ascending aorta[28] [Figure 12]. Although the clinical impact of rotational positioning on procedural durability and the biomechanics of the neo-root remains unclear, its implications for the location of the cardiac conduction system and the risk of iatrogenic injury are noteworthy. In the context of clockwise rotation, the inferoseptal recess becomes wider and deeper. This configuration displaces proximal ventricular components downward and outward, beyond the basal ring plane. In this scenario, the left bundle branch is situated more inferiorly and posteriorly relative to the nadir of the right coronary leaflet. Conversely, counterclockwise rotation narrows and shallows the inferoseptal recess, drawing these components inward and within the basal ring. This configuration increases the risk of iatrogenic damage[29-32].

POSTOPERATIVE EVALUATION

Following aortic valve repair or aortic root reconstruction, a postoperative cardiac CT scan may be considered. However, we do not recommend its routine use, as its clinical benefits and cost-effectiveness have not been clearly demonstrated. Nevertheless, it should be noted that pre-discharge imaging is generally advised in patients undergoing aortic surgery. Additionally, cardiac CT may serve as a valuable tool in specific clinical scenarios or for research purposes. In this section, we outline its main applications.

Detection of complications

As with any surgical procedure, if symptoms or clinical examinations raise suspicion of complications, imaging assessment is warranted. This principle also applies to aortic valve repair and root reconstruction. Moreover, certain silent yet potentially serious complications can be detected by routine postoperative CT scans. These include coronary button dehiscence, pseudoaneurysms, and coronary artery compression [Figure 13]. The latter is more likely when external aortic annuloplasty is performed.

Neo-root and functional anatomy

After ruling out complications, the goal of a postoperative CT scan is to evaluate the new (neo-) anatomy and functional structure of the aortic root. Following the step-by-step approach described above, it is possible to re-assess all components of the aortic root-valve complex[31]. The aortic neo-annulus typically appears smaller and more circular[15], reflecting the effects of annuloplasty or reimplantation procedures. The characteristics of the valve leaflets can be analyzed in terms of eH, gH, and cL[17], and the orientation of the commissures can also be verified. These parameters are essential not only to confirm the success of the procedure, but also because reduced eH and gH are associated with an increased risk of valve failure and recurrent regurgitation[23]. Additionally, leaflet symmetry (particularly in BAV), whether present before or after surgery, has been linked to long-term procedure failure[33,34]. Identifying these risks early may facilitate more vigilant follow-up and timely intervention.

Technique comparison

As aortic valve repair techniques have gained broader adoption, a wide variety of surgical approaches have emerged. However, most reported experiences originate from single centers (or even single surgeons), leading to potential biases and limited control over confounding factors[35].

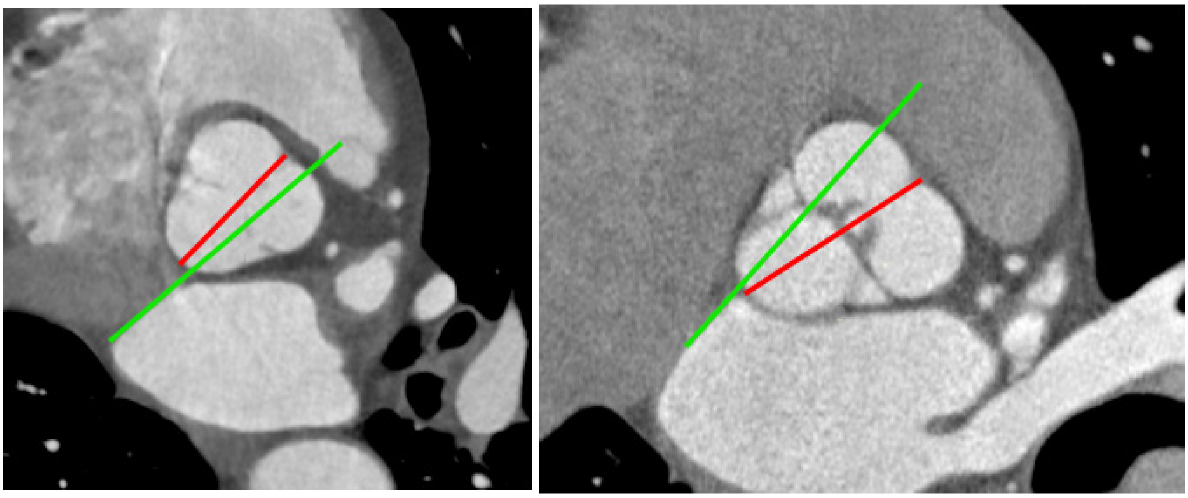

Figure 12. Double oblique MPR showing two different rotational positions. Red lines connect the non-coronary sinus with the opposite commissure; green lines represent the virtual continuation of the interatrial septum (atrial buttress). Left: root rotated ~5° counterclockwise; right: root rotated ~15° clockwise (radiological view). MPR: Multiplanar reconstruction.

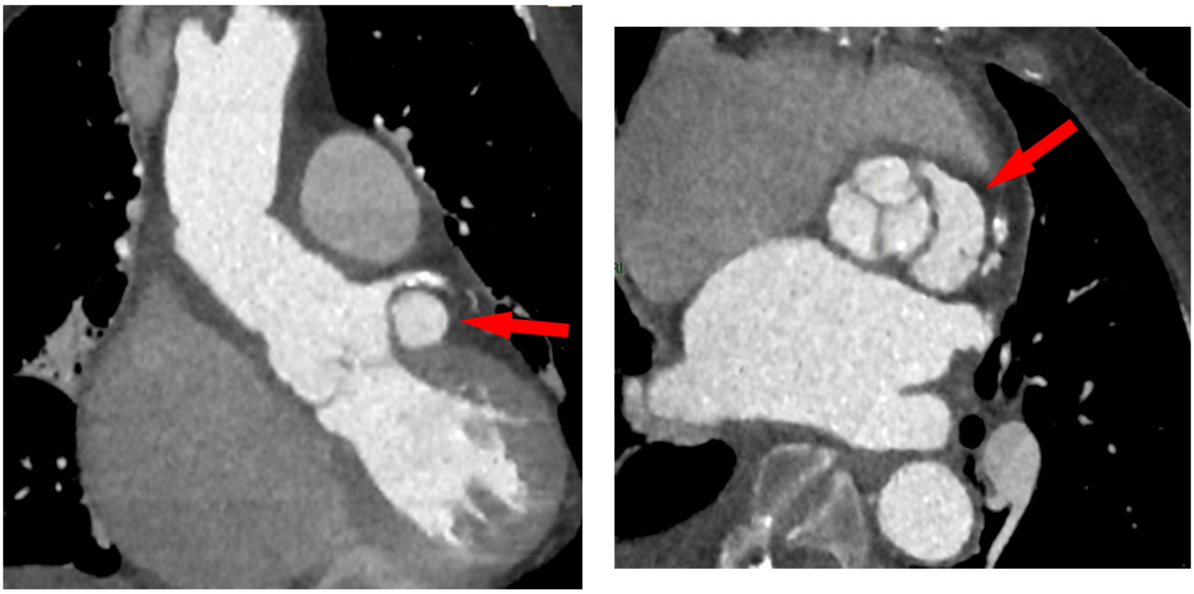

Figure 13. Postoperative CT scan showing an aortic annulus pseudoaneurysm (left: double-oblique cut parallel to the vessel axis; right: double-oblique cut perpendicular to the vessel axis) - red arrow. CT: Computed tomography.

Beyond reporting clinical outcomes, it is critical for surgeons using these techniques to share and compare their results to facilitate ongoing refinement and standardization. In this context, well-conducted pre- and postoperative cardiac CT assessments can yield objective and reproducible data on the geometry and functional anatomy of repaired valves, thereby supporting more physiologically and functionally meaningful comparisons.

LIMITATIONS

Although CT is a valuable tool for anatomical assessment and surgical planning in cardiac procedures, its use is limited by several factors. One major concern is exposure to ionizing radiation, particularly in younger patients or those requiring repeated imaging. Additionally, the risk of contrast-induced nephropathy warrants caution in certain patient groups. The high cost of CT also affects its overall cost-effectiveness, particularly when the clinical benefit is marginal. Moreover, CT predominantly provides static images and has limited capability for real-time or dynamic functional assessments, such as evaluating valvular motion or myocardial contractility. In contrast, echocardiography (transthoracic or transesophageal) offers dynamic, bedside evaluation of cardiac function without radiation exposure. Cardiac MRI provides both high-resolution anatomical detail and advanced functional assessment, albeit with higher costs, longer acquisition times, and limited availability. These limitations underscore the necessity of customizing imaging strategies to the specific diagnostic and procedural needs of each patient[36].

CONCLUSION

Cardiac CT enables a step-by-step assessment of the aortic root, which is essential for accurate surgical planning. The process begins with evaluating the overall dimensions and shape of the ascending aorta, sino-tubular junction, and aortic root. This is followed by an assessment of the aortic annulus, including its shape and size, and a detailed evaluation of the valve, such as the number of cusps, morphology, and quantitative measurements. CT also provides clear visualization of the surrounding structures of the left ventricular outflow tract and coronary arteries, enabling a comprehensive approach to aortic valve-sparing procedures. Postoperative CT can aid in diagnosing complications, comparing surgical techniques, and refining procedural strategies. This systematic, stepwise approach enhances surgical precision and improves outcomes in patients with aortic root pathology.

With ongoing technological advancements, the capabilities of cardiac CT are expected to expand further. Photon-counting CT, with its superior temporal and spatial resolution, will enable precise characterization of structures throughout the cardiac cycle, effectively offering 4D imaging. Additionally, the integration of AI and machine learning may enable semi-automatic assessments of aortic root and valve features relevant to repair, potentially facilitating earlier identification of the most suitable surgical techniques and predicting associated risks of failure.

DECLARATIONS

Authors' contributions

Original draft: Irace FG
Revision: Chirichilli C
Validation, supervision: de Paulis R

Availability of data and materials

Not applicable.

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Conflicts of interest

de Paulis R is the Guest Editor of the Special Issue "Innovations in Aortic Surgery and Valve Repair" of the journal *Vessel Plus*. de Paulis R was not involved in any steps of editorial processing, notably including reviewer selection, manuscript handling, or decision making. The other authors declared that there are no conflicts of interest.

Ethical approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

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