Thoracic and Cardiovascular Surgery

Pre- and Postoperative Imaging of the Aortic Root for Valve-Sparing Aortic Root Repair (V-SARR)

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Valve-sparing aortic root repair (V-SARR) using the David reimplantation method is an increasingly popular alternative to composite valve graft aortic root replacement in patients with aortic root aneurysms or dissections who wish to avoid anticoagulation. Computed tomography (CT) with retrospective electrocardiograph (ECG)-gating has become routine before and following V-SARR at Stanford. CT allows accurate measurement of aortic dimensions and provides unprecedented three-dimensional (3D) images of the sinuses, the aortic valve cusps, and coronary arteries in patients with the Marfan syndrome (MFS), with a bicuspid aortic valve (BAV), or other aortic diseases. This helps the surgeon to conceptualize the size of the aortic grafts required and how much reduction is necessary proximally (aortic annulus) and distally. These maneuvers are used to reduce the aortic annular diameter (when necessary) and replace the sinuses and ascending aorta (T. David-V, Stanford modification V-SARR). Postoperative ECG-gated CT confirms the reconstructed geometry and reliably detects coronary or other anastomotic problems.
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The traditional surgical method of aortic root replacement in patients with aneurysms or dissections involving the aortic root and ascending aorta utilizes a single graft that contains a mechanical valve, the so called "composite valve-graft" (CVG), and reimplantation of the coronary artery ostia.[1] Over more than 30 years, CVG has become a low risk and very durable procedure.

One increasingly popular alternative to CVG for patients wishing to avoid anticoagulation is valve-sparing aortic root replacement. The basic idea is to replace the walls of the aortic root, but preserve the patient's own valve. Again, the coronary ostia need to be reimplanted. The various techniques of valve-sparing aortic root replacement can be categorized into two broad groups[2]: the Yacoub "remodeling" procedure (where a scalloped graft is sewn to the residual portions of sinus tissue along the cusp hinges[3]), and the Tirone David 'reimplantation' procedure (where the proximal graft anastomosis is anchored at the ventriculo-aortic junction below the level of the cusps, and the valve is sewn inside the graft[4]). The reimplantation technique is associated with a very low rate of valve-related complications.[5]

At our institution, a variant of the Tirone David[4] reimplantation technique (T. David-V, Stanford modification) using two separate grafts, has been preferred since December 2002[2] (Fig. 1), which gives the surgeon unlimited flexibility to individualize the dimensions and 3D geometry of the root reconstruction according to the patient's specific pathoanatomy and creates "neo-sinuses" in the vascular graft mimicking sinuses of Valsalva (SOV) (Fig. 2).

The main patient groups treated with V-SARR at our institution are patients with Marfan syndrome (MFS) and patients with bicuspid aortic valve (BAV)-associated aneurysms. Preoperative imaging and visualization with accurate measurements help the surgeon to conceptualize the size of the graft used, which is "necked-down" (plicated) proximally to create whatever new annular size is necessary. Imaging also facili-

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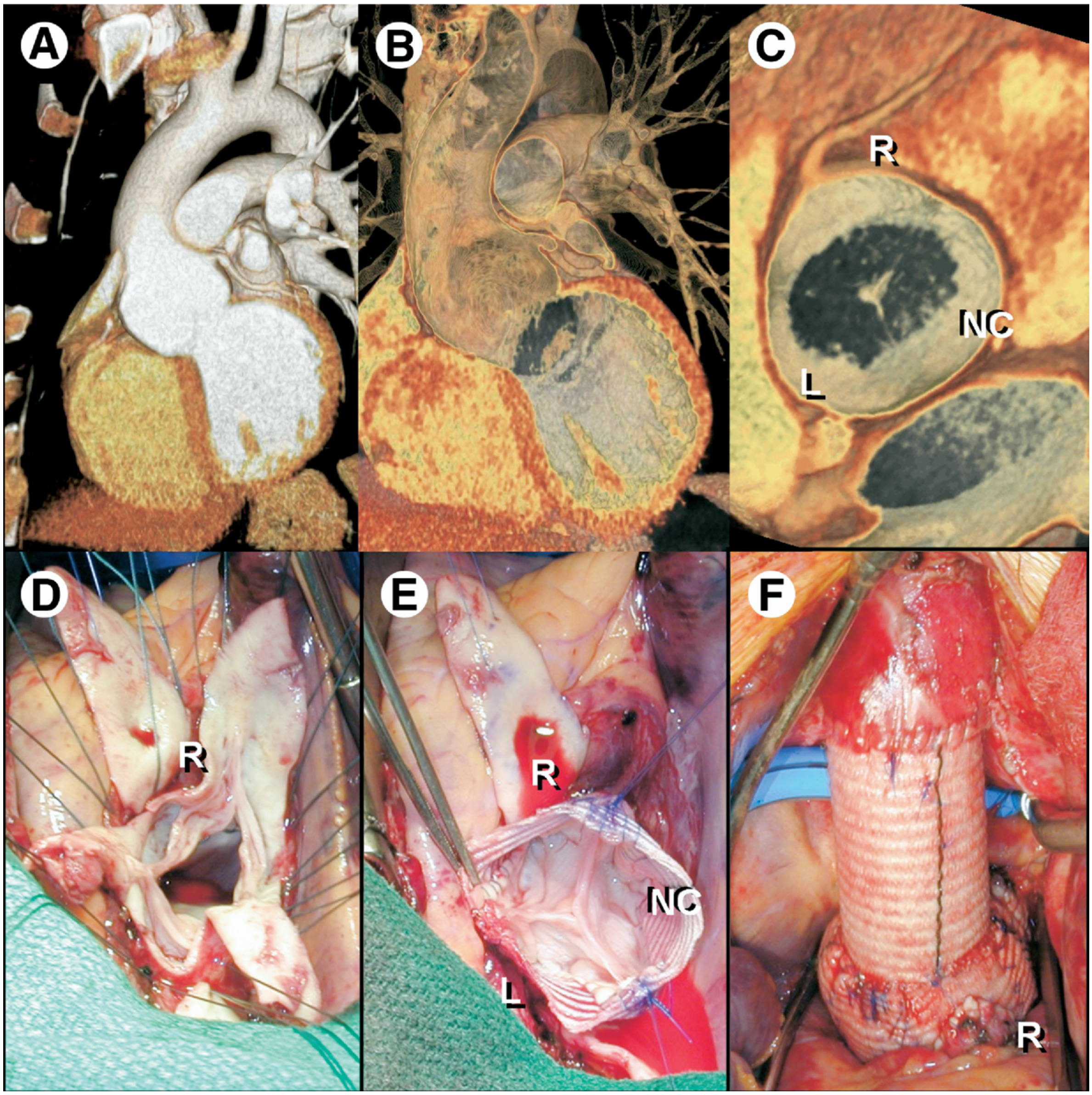
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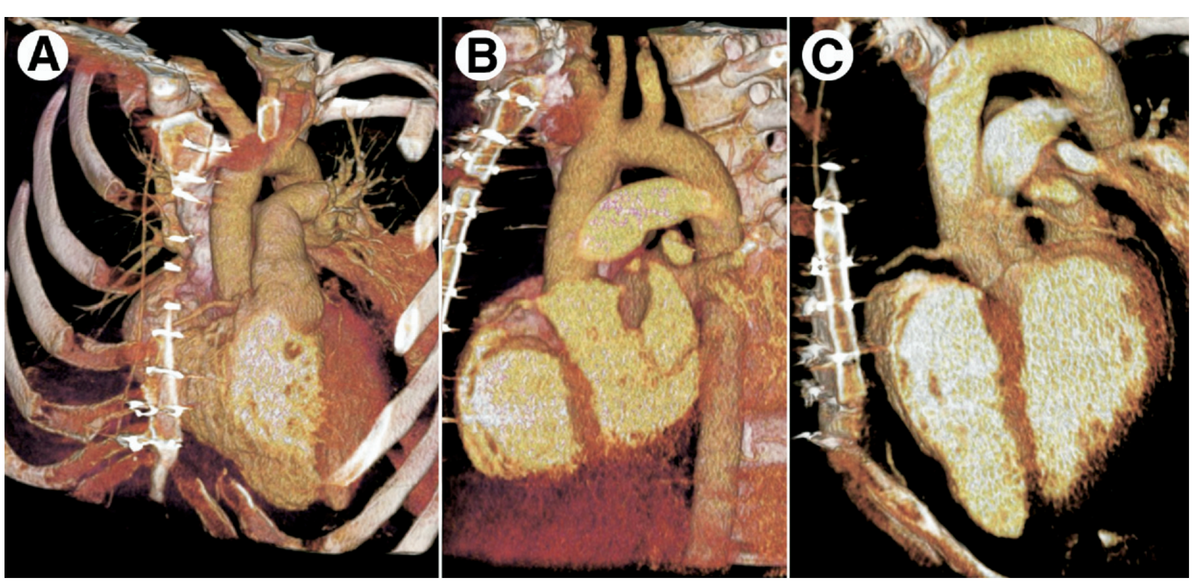
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tates judging the appropriate diameter and height of the graft neo-sinuses and the size of the second graft above the neo-sinotubular junction.

Imaging Technique and Postprocessing

Electrocardiograph (ECG) gated computed tomographic angiography (CTA) of the thoracic aorta has become an integral part of our preoperative workup of patients undergoing V-SARR. As described in more detail elsewhere in this issue, this technique provides high-resolution 3D datasets of the aorta at arbitrarily chosen phases of the cardiac cycle. ECG gated acquisition is particularly important for evaluation of the aortic root since there is significantly greater motion of the root than other parts of the aorta. This enables motion-free static visualization of moving structures, such as the heart and the aortic root, and it also allows to "cine-view" through the cardiac cycle and observe 3D structures over time ("4D").

The two main strengths of this technology in the setting of V-SARR are the ability to obtain reliable measurements of the aortic root and contiguous structures in any arbitrary orientation. The ability to generate arbitrary oriented (orthonormal) images to augment the axial images is critical in assessing the size of the aortic root since the aortic root is typically located oblique to standard axial slices. The data gathered may also be post-processed to generate unprecedented 3D images of aortic root anatomy and pathology. Modern post-processing workstations or, as in our institution, a server-client based system, allow interactive manipulation and interrogation of the datasets as part of image interpretation. The specific post-processing techniques used at our institution for evaluating patients before V-SARR are listed in Table 1. The value of 3D and 4D image processing cannot be overstated, notably for the evaluation of complex pathology. Another enormous benefit of 3D visualization is the opportunity to discuss a surgical procedure with a patient using his or her own pictures and movie clips. It is not only for the physician, but even more so for a patient that such pictures can say more than a thousand words.

Anatomy, Pathology, and Terminology of Aortic Root Diseases

A written report is the most traditional form of conveying information of an imaging study to the ordering physician, and it is important that a common terminology is used, and that the meaning of reported measurements is unambiguous.

When the diameter of the aortic annulus exceeds 27 mm and the SOV are enlarged, the term "annuloaortic ectasia" is used. For practical and imaging purposes it is also sufficient to define a thoracic aortic aneurysm using a single diameter as a threshold. We use the term aneurysm for any aortic segment (SOV, sinotubular junction, ascending, transverse arch, and descending thoracic aorta) with a diameter larger than 4 cm. The terms (mild/moderate) dilation or ectasia are used for apparently wider segments that are smaller than 4 cm in diameter. While chosen empirically, the ~4 cm upper limit of normal has recently been confirmed in a large retrospective study using ECG gated datasets.[6] The plan for patients with a borderline aneurysmal aorta is usually just regular surveillance follow-up and β blockade therapy.

Morphologically, thoracic aortic aneurysms can be described as saccular, fusiform, or diffuse. The most important descriptors, however, are the maximum diameter and the anatomic extent relative to the above mentioned segments. An aortic root aneurysm, ascending aneurysm, arch aneurysm, descending aneurysm, or any combination thereof, each has its respective surgical implications.

The maximum diameter of a thoracic aortic aneurysm is an important predictor for the risk of dissection or rupture. In asymptomatic patients with MFS and other heritable aortic diseases, surgical repair generally is recommended when the maximum aneurysm diameter approaches 5 cm (2.75 cm/m^2 body surface area),[7] or even smaller if the patient has a positive family history of aortic catastrophe. In patients with degenerative or atherosclerotic aneurysms, surgical repair is usually indicated when the maximum aneurysm diameter reaches 6 to 7 cm in the absence of symptoms or documented enlargement.

Figure 1 Valve-sparing aortic root replacement in MFS. Preoperative volume rendered image (A) of the thoracic aorta in a 27-year-old man with MFS shows aortic root aneurysmal dilation. Transparent-blood rendering (B) and a view from above the valve ("anesthesiologist's perspective") (C) illustrate considerable dilation of the SOV. Intraoperative photographs demonstrate (D) the aortic valve and the residual sinus tissue surrounding the commissures after resection of the SOV. Note the sutures through the ventriculo-aortic junction in the left ventricular outflow tract, which will be used to anchor the graft. The excised right coronary artery button (R) with the ostium is seen. In (E), the aortic valve is seen resuspended within the proximal graft which has been anchored to the ventriculo-aortic junction (not shown). An anterior view of the completed reconstruction (F) of the aortic root with the Dacron neosinuses and the reimplanted right coronary artery (R), and the second tube graft replacing the tubular portion of the ascending aorta which recreates a smaller new sinotubular junction. L, left coronary sinus; NC, noncoronary sinus.

Figure 2 Normal postoperative CT after valve-sparing aortic root replacement. Postoperative volume rendered images (A)–(C) in the same 27-year-old man with MFS as in Fig. 1 shows normal ascending aortic graft (A), (B), and larger aortic root graft with "neo-sinuses" (B), (C), and patent coronary artery button anastomoses (C).

Table 1 Postprocessing Techniques and Parameters for Preoperative Visualization of the Thoracic Aorta

	Rendering Technique and Parameters	Views/Images
Aorta, 3D overview (Fig. 1A, Fig. 2)	VR, 5 to 8 cm thick slab, CTA-transfer function (opaque vessels)	"Candy cane" view; usually a LAO projection; shows which segments are involved, and shows position and orientation of aorta in the chest
Chest wall, 3D (Fig. 3A, B)	VR, full volume or slab; adjust transfer function to visualize bony and cartilaginous portions of the ribs	In patients with scoliosis and pectus excavatum, and in all redo procedures, to show position of heart and vessels, notably the right coronary artery, relative to the sternum
Aorta, diameters	Thin slab MIPs (5 mm) in ascending, transverse, and descending aorta MPR orthogonal	Thin slab MIPs obtained in LAO view; more than one image required in very tortuous aorta. "True" diameters should be obtained from MPR images oriented normal to the vessel axis if needed (e.g., stent-grafting)
Aortic root, 3D and 4D (Fig. 1C, Fig. 3E, F, Fig. 4B, Fig. 5A)	VR, 2 to 4 cm slab, transfer function adjusted to render vessel lumen transparent, adjustments needed to display calcifications as well	View directed at the valve from above ("anesthesiologist perspective"). Provides "inside" view of the "hollow" sinuses, coronary origins, and aortic valve. Capture systolic and diastolic views, as well as a cine-loop movie clips of aortic valve
(Fig. 5B)	Thin slab MinIP (1 to 3 mm); inverted gray-scale or thin slab MIP (1 to 3 mm) if calcified	
Aortic root, measurements (Fig. 4A)	MPRs or thin MIPs, annulus, sinuses of Valsalva, sinotubular junction	Oblique coronal and LAO (~3-chamber) views, with plane through center of valve. Orthonormal measurements (e.g., at sinuses of Valsalva level)

VR, volume rendering; CTA, computed tomographic angiography; LAO, left anterior oblique view; MIP, maximum intensity projection; MinIP, minimum intensity projection; MRP, multiplanar reformation.

Timing of surgical intervention should not be determined, however, based on a single absolute aortic measurement. Consideration of the degree of enlargement relative to the "normal" aortic size should be included in the decision-making process. One approach adopted by us and other surgeons is the "2×" rule where the diameter of a contiguous normal aortic segment is the denominator and the maximal aortic size is the numerator; if this ratio exceeds 2, consideration of surgical (or stent-graft) repair is warranted as the risks of operation usually are less than the risk of aortic catastrophe within the next year. This normalizes the dilated segment to the patient's normal aortic size and is valid in petite women as well as in large men. Other factors, including the etiology of the aneurysm, a family history of aortic dissection, or enlargement of the aneurysm should also be considered. In patients with MFS who have a positive family history of aortic catastrophe in centers with a documented clinical track record of successful valve-sparing aortic root replacement with an operative mortality risk less than 1%, prophylactic operation is indicated when the aortic root is even smaller than 2× the size of the normal distal ascending aorta.[8] Other methods include normalizing aortic size to BSA or using the area of the maximally dilated segment (cm^2) divided by the patient's height (in meters) (if >10 cm^2/m, then operation should be considered). The indication for elective surgical repair of aortic root aneurysms is also modulated by the presence and degree of aortic valve incompetence due to stretching and subsequent mal-coaptation of the valve cusps.[9] Of note, the term "sinus of Valsalva aneurysm" applies to aneurysms of a single sinus, rather than a dilation of all sinuses (which should be described as root aneurysm).[10]

Etiology of Aortic Root Diseases

The etiology of aortic root aneurysms and dissections is dominated by inherited disorders and syndromes. A majority of patients undergoing aortic root replacement at our institution have either MFS or BAV-associated aneurysms.

Progressive aortic root dilation leading to aneurysm and dissection is the leading cause of morbidity and mortality in patients with MFS. Thoracic aortic dissection occurs in 40%, justifying prophylactic aortic root and ascending aortic repair. Valve-sparing aortic root replacement represents a reasonable alternative to CVG repair in some patients. Survival is excellent and complications are rare with both techniques, but the long-term durability of valve-sparing aortic root replacement has yet not been fully established.

BAV has a high incidence of 1:100 (4 million in U.S.), with a 4:1 male predominance, familial aggregation, and is associated with coarctation of the aorta, patent ductus arteriosus, and cor-

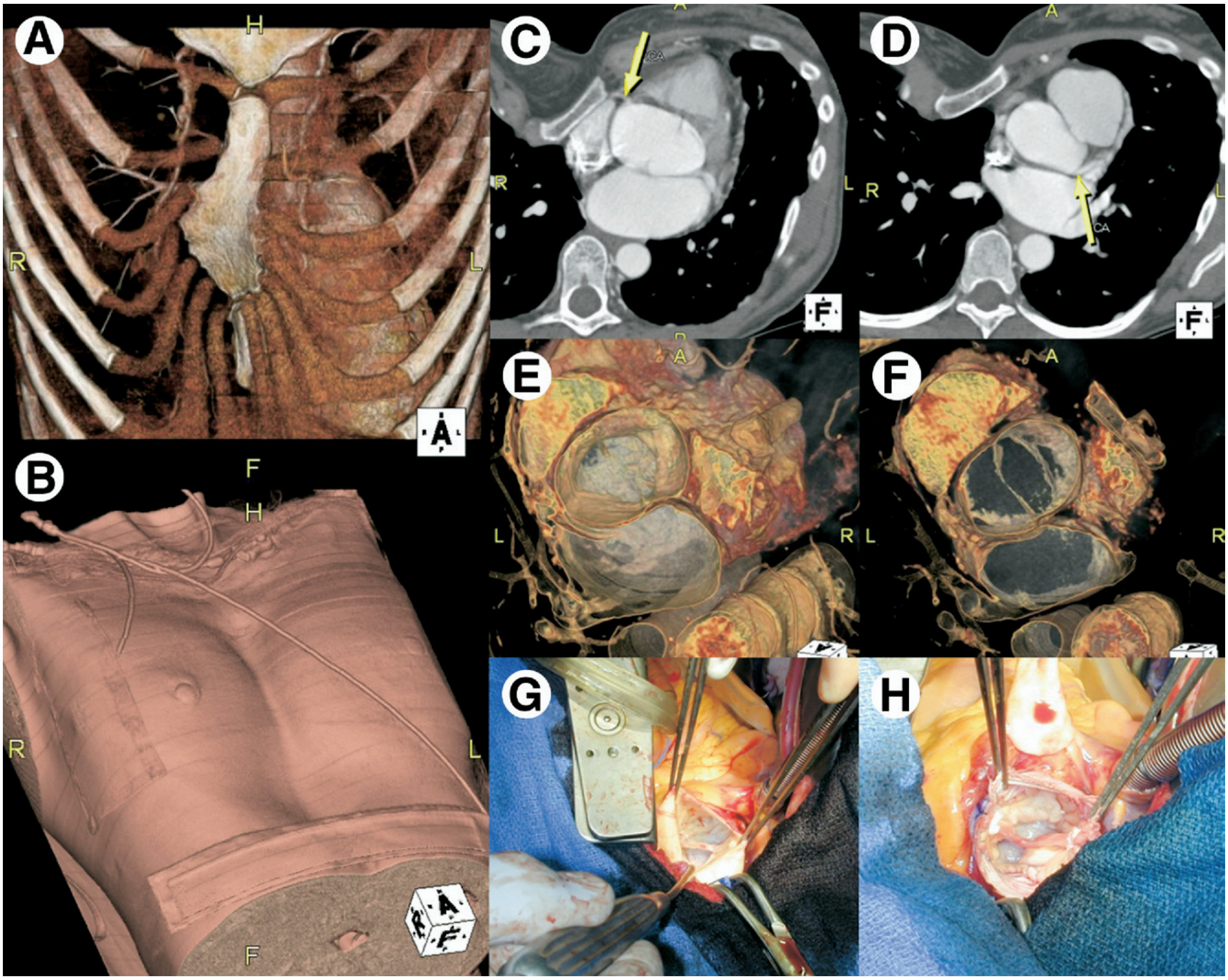

Figure 3 Preoperative CT before V-SARR in a young woman with MFS and a BAV. Volume rendering of anterior rib-cage (A) and skin surface (B) shows marked pectus excavatum morphology. Transverse CT images (C), (D) show origins of the right coronary artery [arrow in (C)], and the left coronary artery [arrow in (D)], and the relationship of intrathoracic structures behind the deformed sternum. Volume rendered "transparent blood" views of the aortic root in diastole (E) and systole (F) illustrate a symmetric bicuspid valve (Sievers' type 0, a-p, formerly termed "naturally perfect BAV"), which was confirmed at operation (G) and was successfully reimplanted (H).

onary artery anomalies. While the most common fate is calcific aortic stenosis (85%) in late mid-life, there is a high prevalence of aortic root enlargement (~50%) irrespective of altered hemodynamics. Root enlargement is considered a precursor to aneurysm formation and dissection, calling for regular surveillance (echocardiography).[11] Aortic dissection occurs in 5%. Aneurysms involve the root, the ascending aorta, and very commonly extend into the transverse aortic arch.[12] Elective surgical repair is indicated when the diameter approaches 5 cm, or when valvular dysfunction occurs. Valve-sparing aortic root replacement is a viable alternative in this group as long as the valve cusps are morphologically intact.

Other less common heritable disorders are Ehlers Danlos (type IV) syndrome, familial aortic aneurysm and dissection, and the Loeys Dietz syndrome.[13] SOV aneurysms are also thought to be caused by a developmental defect. This is supported by the frequent association with VSD (30% to 60%), BAV (~10%), and other congenital abnormalities. SOV aneurysms most commonly originate from the right sinus (65% to 85%), less commonly from the noncoronary sinus (10% to 30%), and rarely from the left sinus (<5%). Other rare causes of aortic root and ascending aortic disease include infectious and inflammatory conditions, such as syphilis and giant cell or Takayasu's arteritis.

Preoperative CTA Image Evaluation

Image interpretation always includes a complete evaluation of the thorax by reviewing the transverse source images. This includes evaluation of the chest wall, lung, and airways, mediastinum, and visualized portions of the lower neck region and the upper abdomen. The specific surgical information sought in preoperative ECG gated CTA of the thoracic aorta is itemized below, and is included in the written radiological report as well as in an accompanying set of representative 2D images, 3D images, and video clips.

Chest Wall and Surgical Access

A 3D display of the chest wall, the rib cage/cartilage and the sternum is particularly helpful in patients with chest wall deformities, such as pectus excavatum or carinatum, which is not uncommon in patients with MFS. Volume rendered display of the chest wall and relative position of the heart and the coronary arteries provides useful preoperative information (Fig. 3). Three-dimensional visualization of the chest wall and mediastinum is also helpful in redo procedures, notably if the surgical details concerning the prior procedure are not adequately documented.

Type and Anatomic Extent of Aortic Aneurysm

One major strength of CT is the ability to convey visually the 3D configuration of the aortic root. Volume rendered images can be generated from any arbitrary viewing angle (Fig. 1 A, B) in addition to a typical “candy-cane view.” Often, a single image illustrates the type and anatomic extent of an aortic root aneurysm (e.g., aortic root aneurysm ± annuloaortic ectasia; ± involvement of ascending aorta; ± tapering into arch). Any gross asymmetry of the SOV, if present, is easily appreciated. CT images also lay out the aortic arch anatomy and branching pattern and can easily depict aberrant vessels or arch abnormalities such as pseudocoarctation, coarctation, venous abnormalities (e.g., persistent left SVC).

Coronary Artery Anatomy (and Pathology)

Preoperative knowledge of abnormal coronary artery anatomy is important, since variants can pose major problems to the surgical repair. Coronary artery anatomy is easily depicted with ECG gated CT. One limitation we have observed occurs in situations of abnormal coronary artery origin where CT cannot reliably distinguish between an intramural course of an obliquely oriented coronary artery versus a coronary vessel wrapped around the aortic root. The image quality of 64-channel ECG-gated CTA of the chest is usually good enough to exclude coronary artery disease in this population with low pretest likelihood, and very few patients need coronary angiography preoperatively at our institution. If extensive coronary artery calcifications are present or if image quality is suboptimal, selective coronary angiography may still be required.

Aortic Valve

Visualization of the aortic valve with its delicate thin leaflets is challenging. Low image noise and good arterial (aortic) contrast medium opacification can routinely be achieved with modern CT, however, and thus permit an exquisite display of the valve cusps, commissures, and sinuses. Our visualization protocol includes volume rendered images of the valve, seen from above (“anesthesiologist’s perspective”) during systole and diastole (Figs. 1, 3 and 4). We also routinely create short cine movie-clips of valve motion, which are critical to distinguish between tricuspid versus bicuspid valves with fused leaflets and a raphé. Bicuspid valves are easily classified with these images. We use descriptive terminology and Sievers’ 2007 classification system[14] (Fig. 3). In addition to volume rendered views, we also generate obliquely oriented cross-sectional views through the aortic root and the valve cusps, which allow better display of valve pathology, such as valve prolapse (Fig. 6), and which also serve as source images for obtaining measurements of cusp dimensions, coaptation abnormalities, and coaptation zone height.

Measurements of the Aorta

Accurate measurements of aortic dimensions are essential for managing patients with aortic root aneurysms. Aneurysm size is a predictor of aortic dissection and is thus, together with valve function, is a key factor in surgical decision-making. The motion-free CT datasets allow accurate preoperative measurements of aortic dimensions in any arbitrary orientation. We measure the aortic root at the level of the annulus, at the SOV, and at the sinotubular junction (Fig. 4). Additional measurements are obtained of the tubular portion of the ascending aorta, the arch, and the descending thoracic aorta. One difficulty in the interpretation of CT derived measurements is that these dimensions do not necessarily correlate well with those obtained using echocardiography. Echocardiograms are limited in the planes in which the root can be measured due to the available echo window, whereas the 3D dataset from a CT provides an infinite degree of freedom in choosing the direction of the dimension to measure across the aortic root. At the level of the SOV, this issue is particularly significant due the irregular shape of the cross section of the aorta at this level and the variable location and orientation of aortic root. Therefore, when monitoring for changes in aortic size, care needs to be taken to make sure that the same orientation for the measurement is used for serial comparison.

Measurements of the Aortic Valve

One critical parameter in the setting of V-SARR is estimation of the appropriate postoperative size of the annulus. The desired annulus diameter is usually determined by intraoperative measurement of the lengths of the aortic valve leaflets from base to free edge and using David and Feindel’s formula.[4] We have retrospectively compared valve measurements obtained from CT data with intraoperative measurements and found a reasonably good correlation (unpublished data), notably in 64-channel CT datasets. With good image quality it is possible to obtain both systolic as well as diastolic length measurements of each leaflet (Fig. 4). The extent of cusp malcoaptation (e.g., prolapse) as well as cusp coaptation zone height also can be appreciated, which is a determinant of valve regurgitation and needs to be enhanced in many patients with aortic regurgitation, especially those with a BAV where pro-

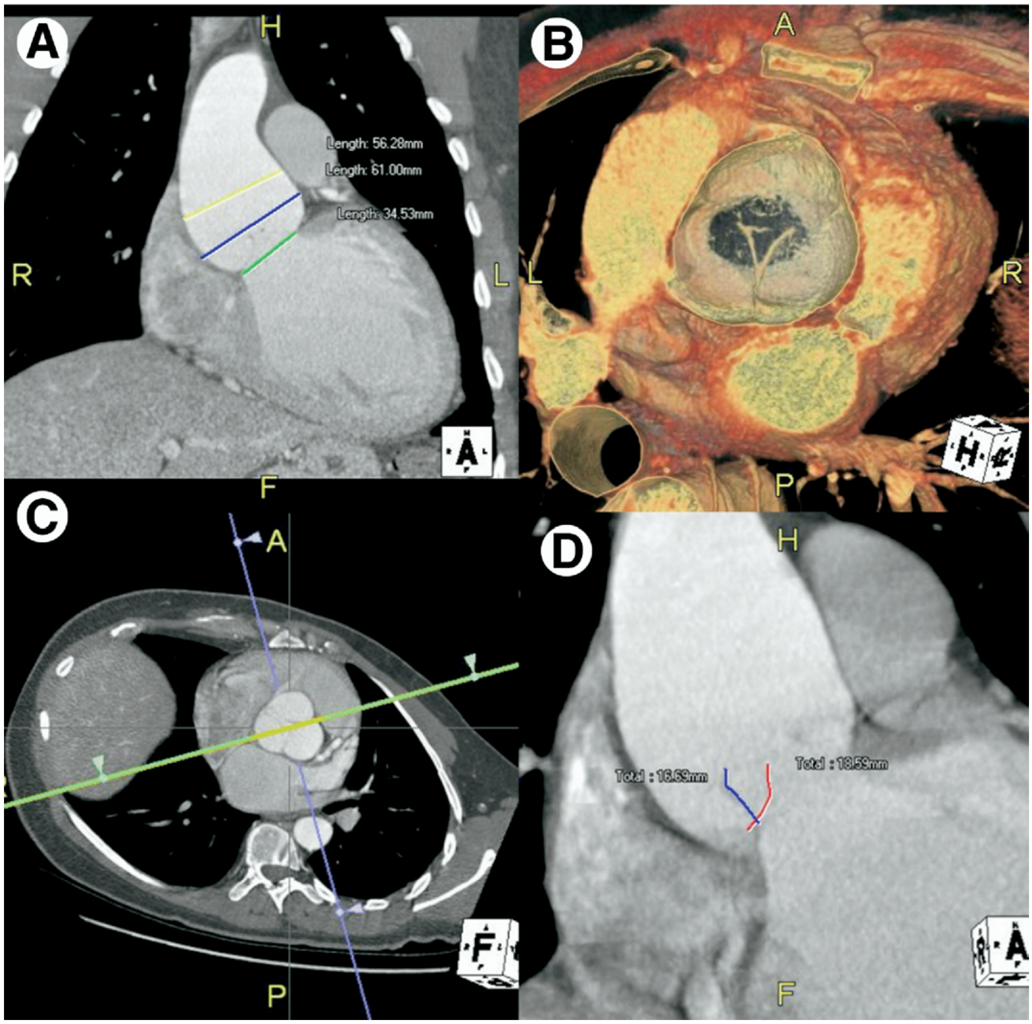

Figure 4 Preoperative measurements using ECG gated CT. Preoperative CT in a 41-year-old man with MFS and aortic root aneurysm. Coronal reformation through the valve center (A) allows measurement of the aortic root at the level of the annulus (35 mm), the SOV (61 mm), and the effaced sinotubular junction (56 mm). Note that the valve leaflets do not coapt at the center in this diastolic frame. The large central coaptation defect is better visualized in the volume-rendered view (B), which also illustrates mild thickening of the free edges of the cusps. Oblique CT reformation through the aortic root at the level of the SOV (C) indicates the cut-plane (green line) through the noncoronary cusp. The corresponding image (D) shows systolic (blue) and diastolic (red) measurements of cusp lengths (~18 mm) of the noncoronary leaflet.

nounced annular dilation is the rule, by reducing the size of the dilated aortic annulus.

Postoperative CTA Image Evaluation

We routinely obtain a predischarge postoperative CT after aortic root replacement with retrospective ECG gating as a baseline for further (nongated) follow-up, which also documents position and orientation of the grafts within the thorax (Fig. 2) and the valve configuration within the graft (Fig. 5E). The most important role of early postoperative CT, however, is to detect complications, such as hematomas or leaks, in regions that are difficult to visualize with echocardiography. CT is particularly helpful to further evaluate and characterize leaks that are seen or suspected on echocardiography (Fig. 6). Side-by-side evaluation of echocardiographic and CT images integrated with knowledge of the surgical details are most helpful in such cases. Nonenhanced postoperative CT images are essential to identify graft material or Teflon strips and pledgets, which are of slightly higher CT attenuation than mediastinal tissues and can be difficult to distinguish from leaks on contrast medium-enhanced images. Postoperative image interpretation specifically attempts to describe the following:

Identification of Grafts

On nonenhanced images, surgical grafts are slightly hyperdense. Also look for Teflon felt strips (used by some surgeons to reinforce anastomoses, but not by us), felt pledgets (reinforced sutures), and BioGlue (after dissection repair), which

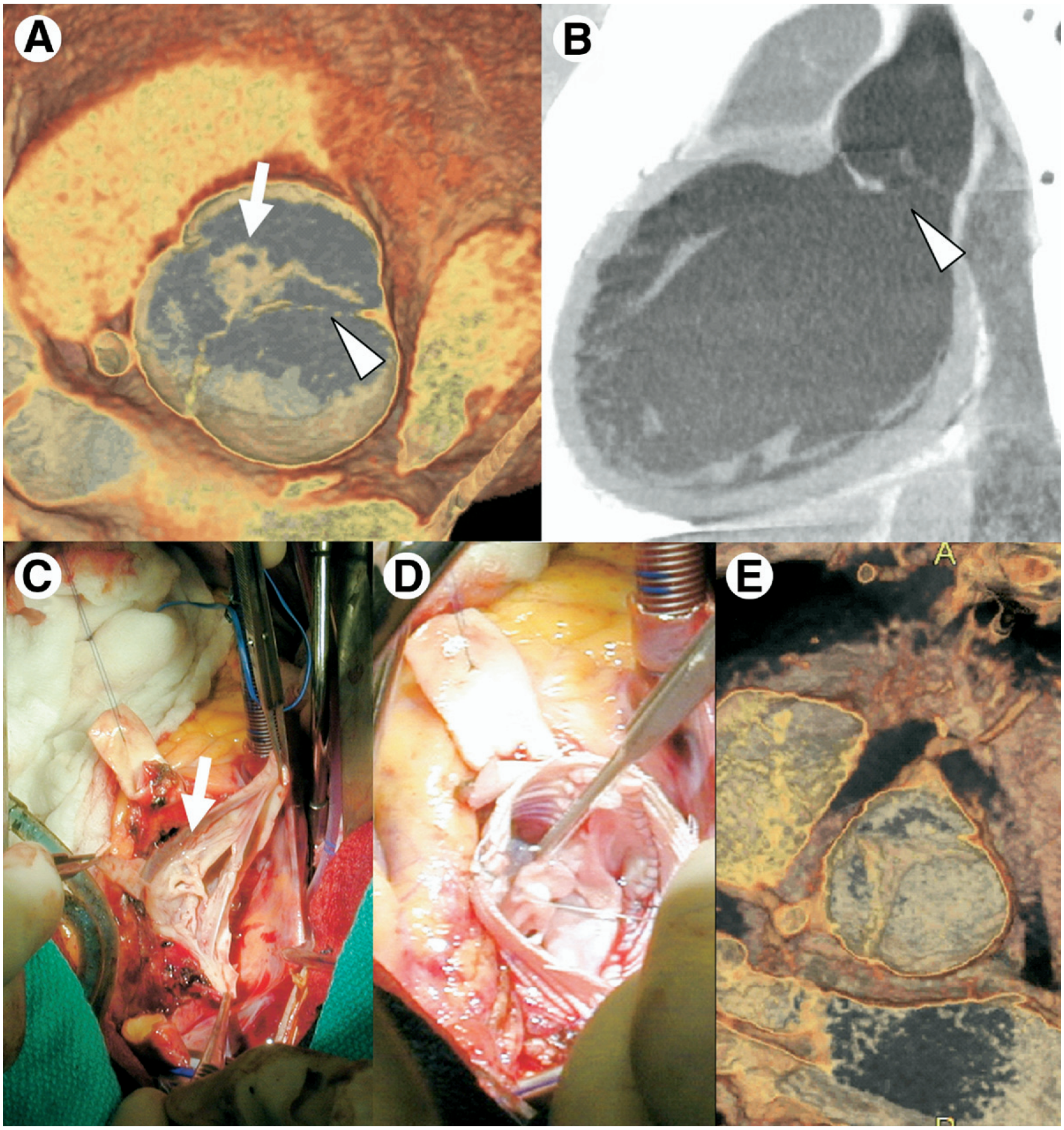

Figure 5 Twenty-seven-year-old man with BAV and aortic root aneurysm. Volume rendered image of the aortic root (A) shows BAV [Sievers type 1, l-r (formerly termed "majority type BAV")] with substantial coaptation defect (arrowhead) between the fused R/L cusp and the NC cusp. Note the unusual circumscribed "thickening" in the region of the raphé (arrow). Oblique minimum-intensity projection (B) shows severe prolapse of the fused R/L cusp (arrowhead) and substantial left ventricular dilation. Intraoperative correlation (C) reveals the "focal thickening" as a torn suspensory chord (arrow) as a cause for the cusp prolapse. (D) Valve-sparing replacement with resuspension of the torn tissue resulting in a competent valve. (E) Postoperative CT image obtained 2 months after surgery shows good valve coaptation.

should not be confused with small anastomotic leaks (on contrast-enhanced images).

Potential Pitfalls

Graft folds (at graft angles, or when a graft is plicated) or a so-called elephant trunk graft in the descending aorta can simulate redissection. Tied-off graft cannulation sites, perfusion graft stumps (e.g., on the right axillary or innominate arteries) or graft limbs (arch) used for cardiopulmonary bypass can mimic small pseudoaneurysms. The right atrial appendage may appear deformed from a purse-string suture after cannulation, which can mimic clot. Small pulmonary emboli are also not infrequently encountered.

Leaks and Pseudoaneurysms

It is imperative to scrutinize proximal, distal, and graft-to-graft anastomoses, as well as the coronary artery Carrel patch or buttons. Small leaks (peri-, supra-, or infra-valvular) may

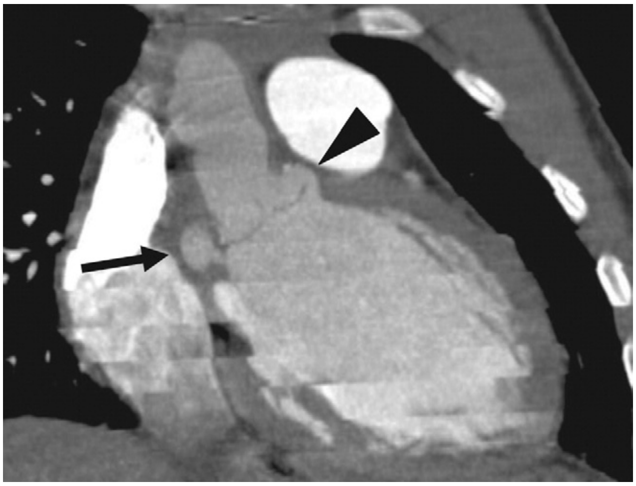

Figure 6 Postoperative complication. Coronal reformation through the aortic root in a 19-year-old patient with MFS after V-SARR performed elsewhere illustrating a small infra-valvular pseudoaneurysm on the right side (arrow) and a small perivalvular leak on the left (arrowhead).

not be visible in all phases of the cardiac cycle. It is helpful to review systolic and diastolic views, which may also provide a clue to the origin of the leak even if the communication is not clearly seen (Fig. 6). Pseudoaneurysms can also occur at arterial or cardiac cannulation sites.

Postoperative Hematoma

Small amounts of retrosternal, pericardial, or periaortic fluid and stranding in the mediastinal fat are normal early postoperative findings.

Infection

Graft infections and sternal osteomyelitis tend to be late complications, and not usually found on early postoperative images, which can be done nongated. Imaging findings range from large abscess-like fluid collections with rim enhancement, contained ruptures, to small amounts of perigraft fluid collections. Minimal soft-tissue density abnormalities may harbor infected and necrotic tissue, and further imaging (white cell scan) should be recommended depending on the clinical circumstances.

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