Multimodality imaging and image guidance techniques for endovascular ascending aortic repair

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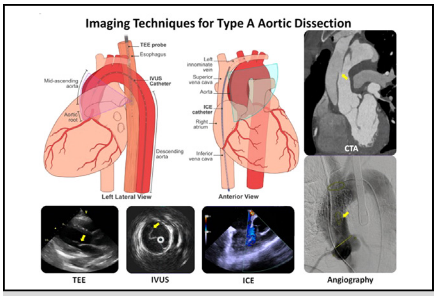
Management of ascending aortic (AAo) pathologies such as aneurysms, pseudoaneurysms, and acute dissections have traditionally been a realm of open cardiac surgery under cardiopulmonary bypass. Recently, there has been a growing interest in endovascular treatment options for AAo pathologies.[1-4] Ascending aortic thoracic endovascular repair (aTEVAR) has evolved from few anecdotal cases to a treatment option with excellent technical success and encouraging outcomes in patients with prohibitive risk for conventional open repair.[5,6] Thoracic stent-grafts, abdominal cuffs, or custom-made grafts such as the Valiant PS-IDE (Medtronic) and Relay Non-Bare Stent (Terumo Aortic) or are most commonly used for aTEVAR in an off-label manner.[5,7-9] Even though there are currently no devices approved by the Food and Drug Administration available, newer endovascular devices are being designed specifically for the AAo.[1,9-11]

The dynamic nature of AAo, with severe angulations, larger diameter with shorter lengths, proximity to coronary arteries, aortic valve leaflets, and pronounced displacement forces during cardiac cycle pose strict morphologic and anatomic criteria for device selection.[12] Understanding the relationship of thoracic aortic aneurysm and dissection intimal flap to the sinotubular junction (STJ) is also critical for aTEVAR. Given these factors, aTEVAR should not be approached as a conventional TEVAR procedure in AAo but with emphasis on better pre- and intraprocedural imaging. This article provides a brief overview of multimodality imaging, intraoperative real-time imaging, and image guidance techniques in the context of aTEVAR.



Different imaging modalities provide accurate depiction of the entry tear and aortic valve.

CENTRAL MESSAGE

CT, fluoroscopy, ultrasound-based imaging, and fusion techniques are complementary for intraoperative guidance in endovascular repair of the ascending aorta and can help achieve techical success.

PERSPECTIVE

Endovascular ascending aortic repair has evolved from a few anecdotal cases to a viable option in patients who are not fit for surgery. Deploying stent-grafts can be challenging in this dynamic aortic segment with severe angulations, overcoming hemodynamic forces, and without impinging aortic valve leaflets. Understanding the interplay between imaging modalities is critical for technical success.

PREOPERATIVE IMAGING

Step 1: Evaluation of Anatomic Suitability

Appropriate patient selection is crucial for aTEVAR, which is typically considered in patients who are poor candidates for open repair. A few potential exclusion criteria include severe aortic insufficiency, the presence of mechanical aortic valve, and patent coronary bypass grafts arising from the AAo (Table 1). Preoperative imaging should help with determining appropriate, proximal, and distal landing zones (LZ), with adequate dimensions and distance of the proximal entry tear

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Abbreviations and Acronyms

2D	= 2-dimensional
3D	= 3-dimensional
AAo	= ascending aorta
ATAD	= Acute type A aortic dissection
aTEVAR	= ascending aorta thoracic endovascular aortic repair
CTA	= computed tomography angiography
ECG	= electrocardiogram
ICE	= intracardiac echocardiography
IVUS	= intravascular ultrasound
MPR	= multiplanar view
MR	= magnetic resonance
STJ	= sinotubular junction
TEE	= transesophageal echocardiography

from STJ (~1-2 cm). To ascertain this key information, an electrocardiogram (ECG)-gated computed tomography angiography (gated-CTA) imaging protocol must be implemented, as conventional nongated CTA scans cannot differentiate motion artifacts from entry tear of acute type A aortic dissection (ATAD) intimal flap[13] (Table 2).

Step 2: Identification of Proximal LZ

To better ascertain the proximal and distal landing zone, orthogonal multiplanar views (MPRs) of AAo are reconstructed using 3-dimensional (3D) postprocessing tools and a semi-automated aortic centerline is computed. Accuracy of aortic centerline is verified (and manually edited if necessary) by scrolling through MPR views and then reconstructed into 2-dimensional (2D) curved-MPR views for accurate length measurements.

Step 3: 3D Planning, Sizing, and Device Selection

Planning for aTEVAR involves assessment of vascular access to deliver the stent graft and selection of appropriate device size. Conventional CTA might miss a proximal entry tear that is mobile, especially if ECG-gating was not performed (Figure E1). While this is performed typically on CTA, real-time imaging with transesophageal echocardiography (TEE) can also be helpful to study the status of ATAD intimal flap and to correlate the measurements from CTA. This highlights the need for covisualizing the TEE images with CTA even before aTEVAR to compare and complement the information from each imaging modality. Once morphometrics are completed, the appropriate oversizing ratio depending on the pathology should be taken into consideration before device selection. In the setting of ATAD, oversizing is minimal, with most authors remaining between 0% and 5% because the treatment goal is to achieve false lumen thrombosis and eventual remodeling of the aorta without risk of rupture.[5] In the setting of aneurysmal/pseudoaneurysmal disease, the radial forces of the stent graft must allow for sturdy fixation onto the healthy

TABLE 1. US-based early feasibility studies (EFS) and clinical trials

	ARISE	EVOLVE aorta (AA arm)	Medtronic valiant
Status	Early feasibility study (FDA IDE G140230)	Clinical trial (NCT0058317)	Clinical trial (NCT02201589)
Device	Ascending Stent Graft	Ascending Aortic Endograft (Zenith Ascend TAA Endovascular Graft)	Valiant with Captivia System
Manufacturer	WL Gore & Associates	Cook Medical	Medtronic
Pathology	a. DeBakey type I/II AD	a. Focal aneurysm in AA b. Pseudoaneurysms and/or dissections that are distal to the STJ c. TAAA ≥5.0 cm in women and ≥5.5 cm in men	a. Type A AD b. Retrograde type A AD, c. Intramural hematoma, penetrating ulcer or pseudoaneurysm of the AA
Device-specific inclusion criteria			
PLZ length	≥20 mm distal to the most distal coronary artery ostium	≥15 mm distal to the most distal coronary artery ostium	≥10 mm
PLZ diameter	24-42 mm	>20 mm and ≤38 mm	28-44 mm
DLZ length	N/A	>5 mm proximal to the IA	≥10 mm
DLZ diameter	24-42 mm	≤42 mm	28-44 mm
Clinical inclusion criteria			
Risk for open repair	High	High or prohibitive	High
Aortic valve	Aortic insufficiency <3+ native aortic valve	N/A	No involvement in the disease

FDA, Food and Drug Administration; *IDE*, Investigational Device Exemption; *AD*, aortic dissection; *AA*, ascending aorta, *STJ*, sinotubular junction; *TAAA*, thoracoabdominal aortic aneurysm; *PLZ*, proximal landing zone; *DLZ*, distal landing zone; *IA*, innominate artery; *N/A*, not applicable.

TABLE 2. Scanning protocols for triple rule-out CTA, aorta CTA, and retrospectively ECG-gated CTA

Parameter	Triple rule-out CTA	Aorta CTA	Retrospectively ECG-gated CTA
Type	Spiral	Spiral	Spiral
Anatomical coverage	Lung apices through diaphragm	Entire aortic vasculature	Aortic arch to cardiac apex
Rotation time, s	0.25	0.5	0.25
Collimation, mm	128 × 0.6	192 × 0.6	152 × 0.6
Pitch	HR dependent	0.6	HR dependent
Tube potential, kV	100	120	120
Effective mAs	CareDose (ref. 288)	CareDose (ref. 288)	CareDose (ref. 288)
Contrast type	Nonionic	Nonionic	Nonionic
Contrast volume, mL	120	120	80-100
Saline flush, mL	30	N/A	30
Injection rate, mL/s	5	4-5	5-7
HU trigger value	230 in ascending aorta	230 in abdominal aorta	230 in ascending aorta
Slice thickness	1-3 mm	1 mm	1 mm
Scan phases	3 phases	Noncontrast, arterial	Arterial, 0%-100% reconstructed at every 5%-10% of R-R interval

CTA, Computed tomography angiography; *ECG*, electrocardiogram; *HR*, Heart rate; *HU*, Hounsfield units.

aortic wall and an oversizing ratio of 20% to 30% is usually considered.[3] Finally, appropriate C-arm angles are preoperatively computed based on CTA, for setting up ideal working projection for device deployment.

INTERVENTIONAL GUIDANCE

Step 4: Vascular Access

The optimal vascular access strategy can be planned better off CTA after assessing vessel size, calcifications, and tortuosity. In patients who cannot undergo CTA, other imaging modalities such as ferumoxytol-contrast magnetic resonance (MR) angiography can be considered.[14] Depending on the diameter profile of stent-graft delivery system, the vascular access can be transfemoral, transapical, or transcarotid/axillary in very rare situations.[3,5] Although femoral access is used in most cases due to its operative ease and surgeon familiarity with it, the long distance to cover as well as iliac artery and arch tortuosity may lead to decreased trackability, pushability, and torquability of the stent-graft delivery system. Transfemoral access is the standard approach, but complications such as iliac artery rupture, dissection, and femoral pseudoaneurysms occur in up to 12.9% of cases.[15] Iliac conduits or endovascular techniques such as "paving and cracking" for smaller diameters or "pull-down" technique for iliac kinking have been described. Transapical access provides the shorter and straighter route to the AA, but some devices have not been designed for retrograde deployment.[16] Transapical access as an alternate option provides a rather direct approach to AAo and can be considered when transfemoral access is challenging. Percutaneous transapical access has been described,[17] but a left minithoracotomy is commonly used. Transaxillary access allows for better accommodation of the stent graft on the inner AA curvature, can be used as a cardiopulmonary bypass bailout access, and is usually less atherosclerotic compared with iliofemoral axes.[18]

Step 5: Image-Fusion and Interventional Guidance

Multimodality imaging and image guidance during interventions has gained further significance due to the recent evolution of transcatheter treatment options for valvular heart disease and complex aortic pathologies.[19] In addition to 2D fluoroscopy, ATAD interventions can benefit when complementary information from multiple imaging modalities can be fused or covisualized to better provide interventional guidance during stent-graft deployment. For example, while aortic root could be better imaged with real-time TEE/intracardiac echocardiography (ICE) imaging, the aortic arch and visceral aorta could be better imaged with intravascular ultrasound (IVUS)/angiography.[20]

Integrating fluoroscopy with CTA after image fusion can provide broader 3D context of catheter/wire position inside aorta and its relationship to branch vessels, before deploying stent-grafts. The clinical benefits of such image fusion techniques have been reported to impact deployment precision and reduction of radiation exposure and contrast medium.[21] CTA–fluoroscopy image fusion can be achieved by 2 approaches: (1) 3D/3D image fusion, where 3D CTA is fused with intraoperative 3D noncontrast cone-beam computed tomography; and (2) 2D/3D image fusion, where 3D CTA is fused with two 2D fluoroscopic images (anteroposterior and lateral/oblique).

During aTEVAR procedures, landmarks such as ostia of coronary/innominate arteries, STJ, and the aortic annular plane are electronically annotated in CTA and overlaid on fluoroscopy for optimizing C-arm angulations before angiography and for interventional guidance (Figure 1). In

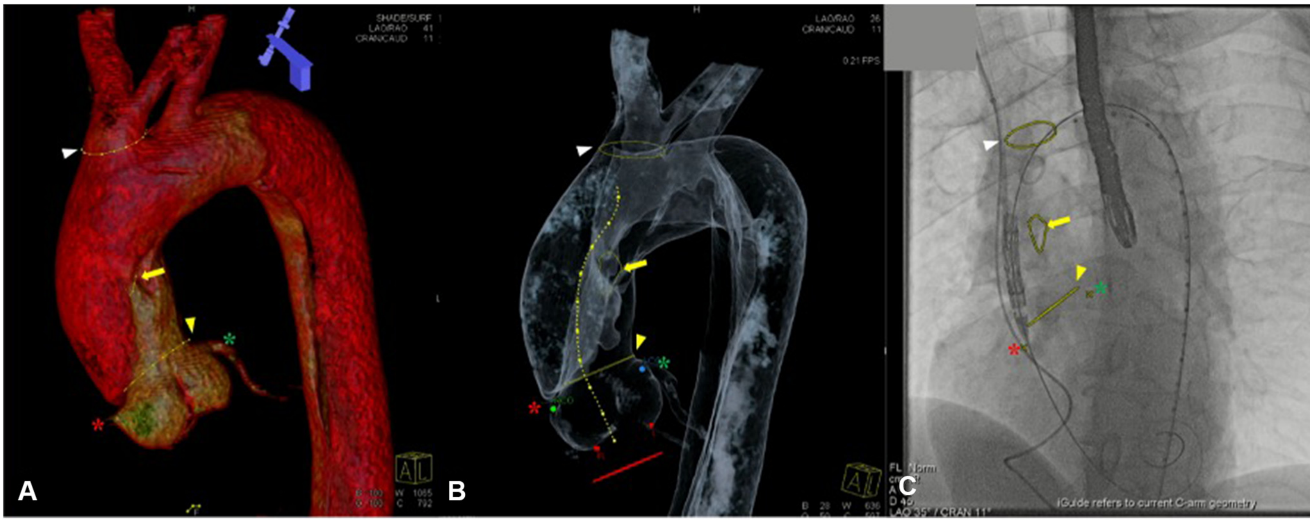

FIGURE 1. CT planning and fusion. Three-dimensional volume-rendered reconstruction of an ECG-gated CTA (A) and translucent rendering (B) of a type A aortic dissection, with an entry tear ~2.5 cm from the sinotubular junction. Anatomic landmarks, such as the *left* (*green asterisk*) and *right* (*red asterisk*) coronary arteries, sinotubular junction (*yellow arrowhead* and *dotted line*), entry tear (*yellow circle*), and innominate artery ostium (*white arrowhead* and *dotted circle*) are marked and overlayed on the fluoroscopic images after CT fluoroscopy image fusion. C, C-arm angulation and image fusion markers on fluoroscopy were used as a guidance to better align and deploy the proximal end of the stent graft. *CT*, Computed tomography; *ECG*, electrocardiography; *CTA*, computed tomography angiography.

thoracic aortic aneurysm and dissection cases, the true/false lumens and site of proximal entry tear can be annotated. Although CTA–fluoroscopy image fusion has been available from different imaging vendors, routine clinical use of this technology is still hampered by current limitations such as an additional learning curve, inaccuracies due to aortic deformation with insertion of stiff guidewires/delivery systems, and patient/respiratory/cardiac movements during the procedure.

Step 6: Intraprocedural Echography

TEE is the primary real-time imaging modality used for guidance during aTEVAR. TEE can also help with device sizing and monitoring any intraprocedural complications

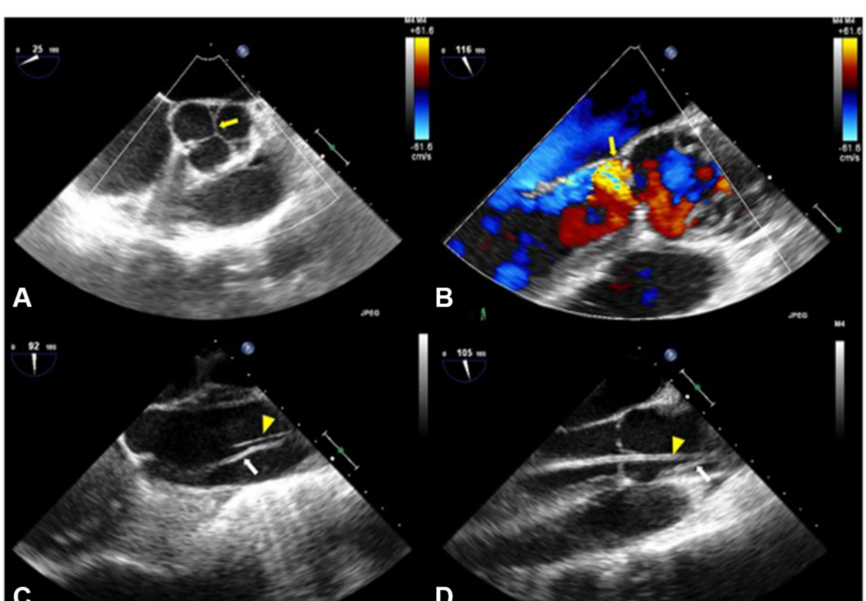

FIGURE 2. Intraoperative transesophageal echocardiographic guidance. Short-axis view showing good coaptation of the aortic valve leaflets (*yellow arrow*) (A) and Doppler ultrasound (B) demonstrating mild aortic insufficiency after crossing the valve with a stiff wire before device deployment. C and D, Long-axis views showing the realtionship of dissection flap to the wire (*yellow arrowhead* indicates dissection flap; *white arrow* shows the wire).

such as aortic regurgitation, hemopericardium (Figure 2). TEE has its disadvantages, including limited imaging for distal AAo, arch and proximal descending aorta due to poor acoustic window, need for general anesthesia, and need for skilled interventional echocardiographers.

ICE is an alternative option to TEE that does not require general anesthesia. Its main advantages include real-time imaging of the aortic valve and AAo, all performed by the physician. Longitudinal views from the cavoatrial junction display the AAo and aortic valve during endograft

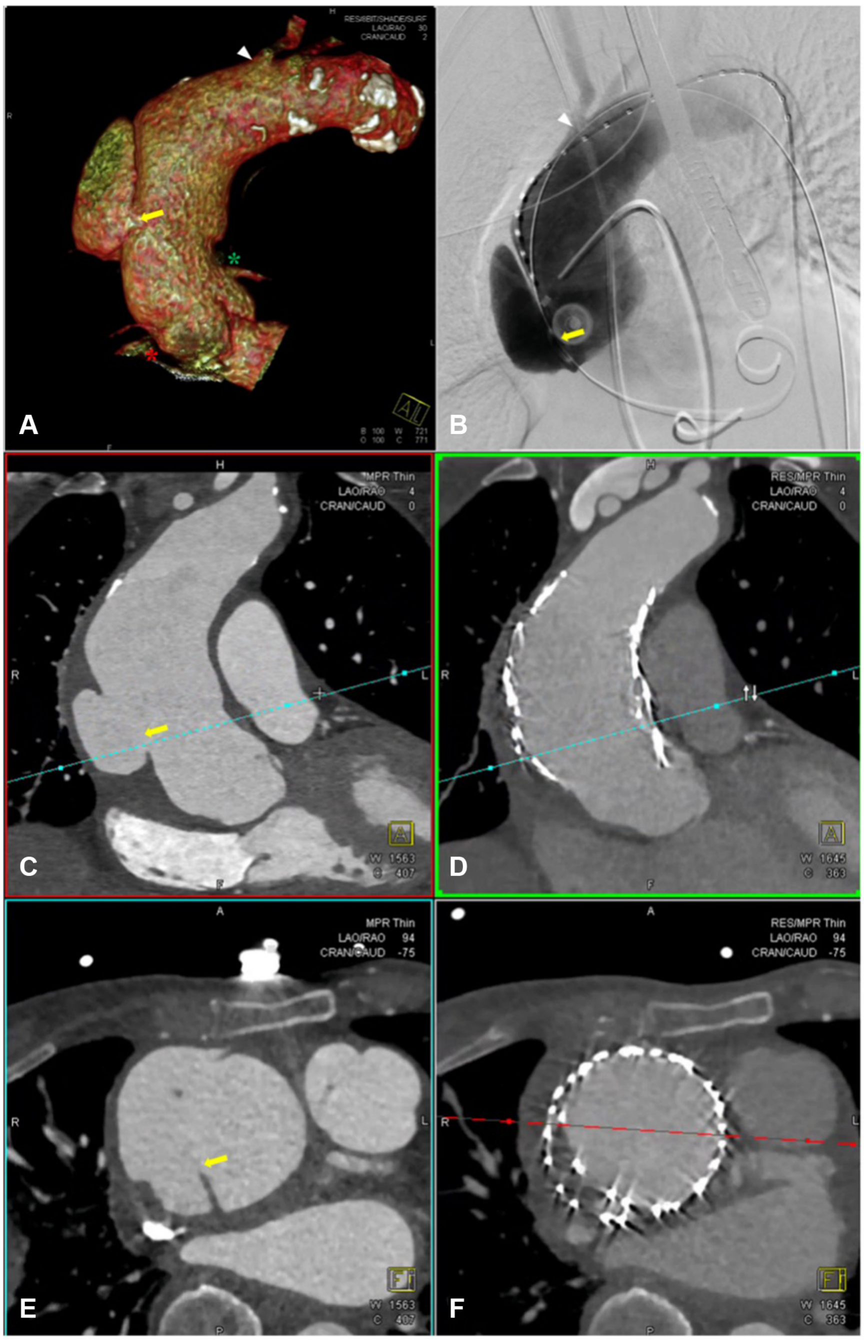

FIGURE 3. Pre- and post-TEVAR comparison. A, 3-dimensional volume-rendered reconstraction of a CTA depicting a penetrating aortic ulcer in the mid-ascending aorta (*yellow arrow*) (A), with its corresponding fluoroscopic view (B). Sagittal and axial view of the pre- (C, E) and postopeartive CTA (D, F) after deployment of stent graft in the ascending aorta, showing complete exclusion. *TEVAR*, Thoracic endovascular aortic repair; *CTA*, computed tomography angiography.

deployment, whereas short-axis views can be used postdeployment to rule out aortic valve regurgitation and any signs of annulus rupture. Limited imaging field-of-view, additional skillsets and catheter cost, catheter oscillation due to cardiac motion, and lack of continuous wave/M modes might limit its routine use.

IVUS is another real-time imaging modality, especially useful in the setting of aortic dissection to understand the wire/catheter position in true/false lumen, and to confirm the findings from CTA imaging or in emergent cases with suboptimal preoperative imaging studies. IVUS also can be used for intraoperative measurement of aortic lumen size and in the setting of hemodynamic instability, as in aortic rupture, when measurements from CTA may be unavailable/inaccurate. IVUS can also provide real-time imaging and assessment of dissection flap and intimal tears. IVUS platform with a stiff 0.035-inch guidewire increases pushability and trackability. IVUS catheters often assume an eccentric position and cannot maintain a stable position to guide device deployment. A coaxial steerable system with fluoroscopic image integration might mitigate these limitations.

Step 7: Device Deployment Under Multimodality Image Guidance

In the current setting, information from multiple imaging modalities such as TEE, ICE, computed tomography, and

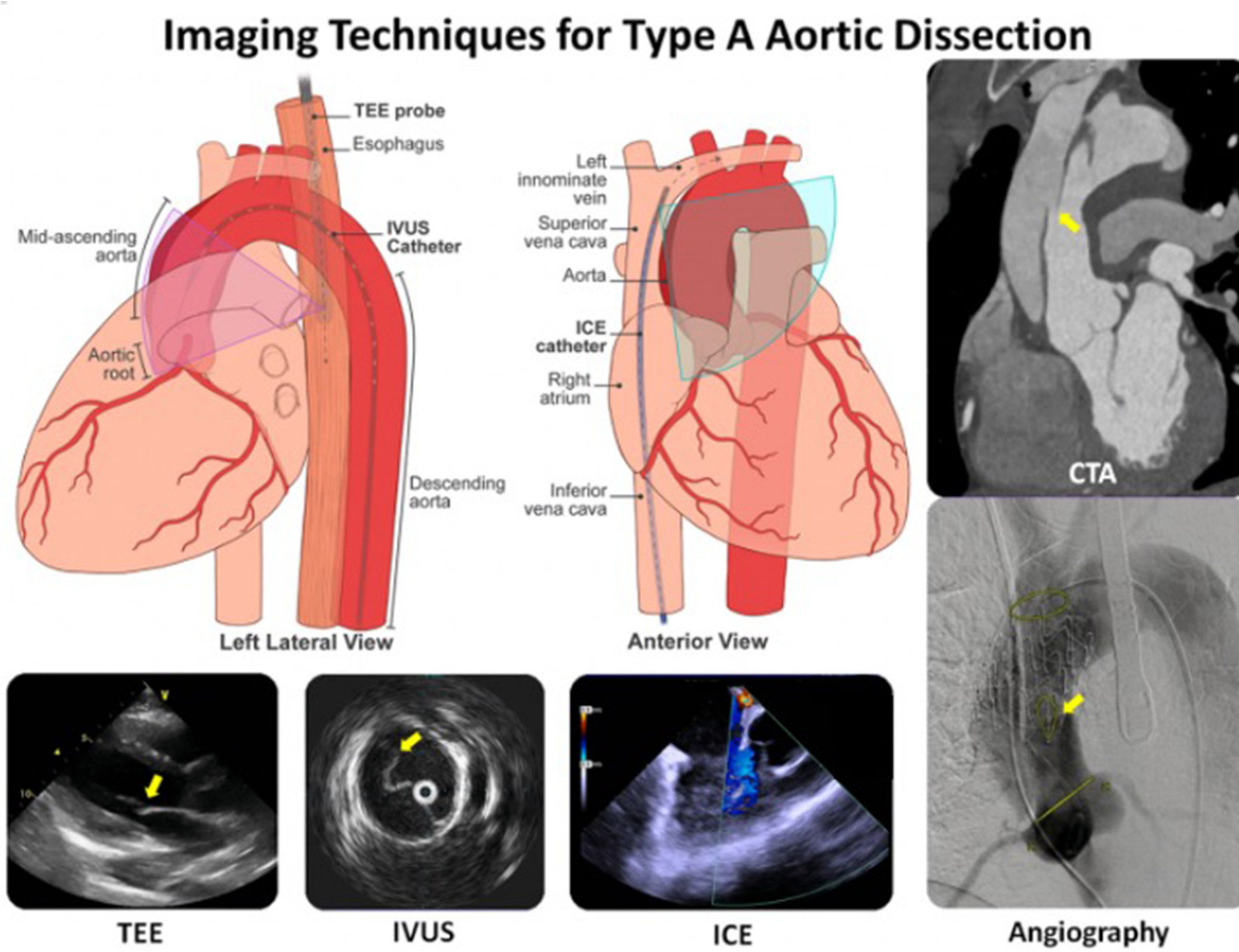

FIGURE 4. Imaging techniques for type A aortic dissection. Ultrasound-based techniques for visualizing the aortic root include TEE, IVUS, and ICE (*illustration*). The illustration depicts the anatomical positioning and field of view of the 3 different ultrasound probes. Clockwise from top to bottom, different imaging modalities illustrate the proximal entry tear of a type A aortic dissection (*yellow arrow*), including CTA, angiography, IVUS, and TEE. The ICE probe focuses on the aortic valve. These modalities are complementary for intraoperative guidance in endovascular repair of type A dissection. *TEE*, Transesophageal echocardiography; *IVUS*, intravascular ultrasound; *ICE*, intracardiac echocardiography; *CTA*, computed tomography angiography.

MR can be overlaid on fluoroscopy to guide endograft deployment over a stiff guidewire. Rapid cardiac pacing is used for attenuating heart movement, although caval ballooning or pharmacologic pacing also can be used.[22] When the correct positioning is achieved, aided by image fusion technology, the endograft is deployed. Conventionally, ballooning after stent-deployment is performed in aneurysmal pathologies but avoided in dissections due to the risk of injury to the acutely dissected, fragile aorta, and migration of the stent-graft along the aorta.[22] No complications have been described in the most current literature[1,3-5,8] during ballooning in the AAo.

Step 8: Postdeployment Imaging

A final digital subtraction angiogram is performed to evaluate stent positioning and the presence of any type 1 endoleaks (Figure 3). TEE/ICE is performed to evaluate aortic valve function.

FOLLOW-UP

Our follow-up regime includes a cross-sectional imaging study at 1, 6, and 12 months and yearly thereafter. The preferred modality is CTA; however, MR is also acceptable, as it reduces radiation exposure for the patients. Follow-up is completed with a full cardiologic and echocardiographic evaluation.

SUMMARY

TEVAR in zone 0 is becoming increasingly relevant. Owing to the dynamic nature of the AAo, better imaging workup is essential for pre-, intra-, and postoperative evaluation. In the near future, novel endovascular devices that can better adapt and conform to AAo will be available. In addition to newer devices, codevelopment of better real-time imaging techniques for valvular regurgitation monitoring is essential. Better integration of multimodal imaging, including but not limited to cardiac CTA, TEE, ICE, and real-time hemodynamic assessment is necessary (Figure 4). Endovascular treatment of ATAD can evolve and merge with an already maturing field of transcatheter aortic valve replacement.

Conflict of Interest Statement

P.C. is a full-time Research Collaborations Manager and Senior Key Expert at Advanced Therapies Division, Siemens Medical Solutions USA, Inc. Both M.J.R. and J.B. are principal investigators for Gore ARISE Ascending aortic stent graft trial. All other authors reported no conflicts of interest.

The *Journal* policy requires editors and reviewers to disclose conflicts of interest and to decline handling or reviewing manuscripts for which they may have a conflict of interest. The editors and reviewers of this article have no conflicts of interest.

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Key Words: multimodality imaging, image guidance, endovascular repair, ascending aorta, TEVAR, image fusion

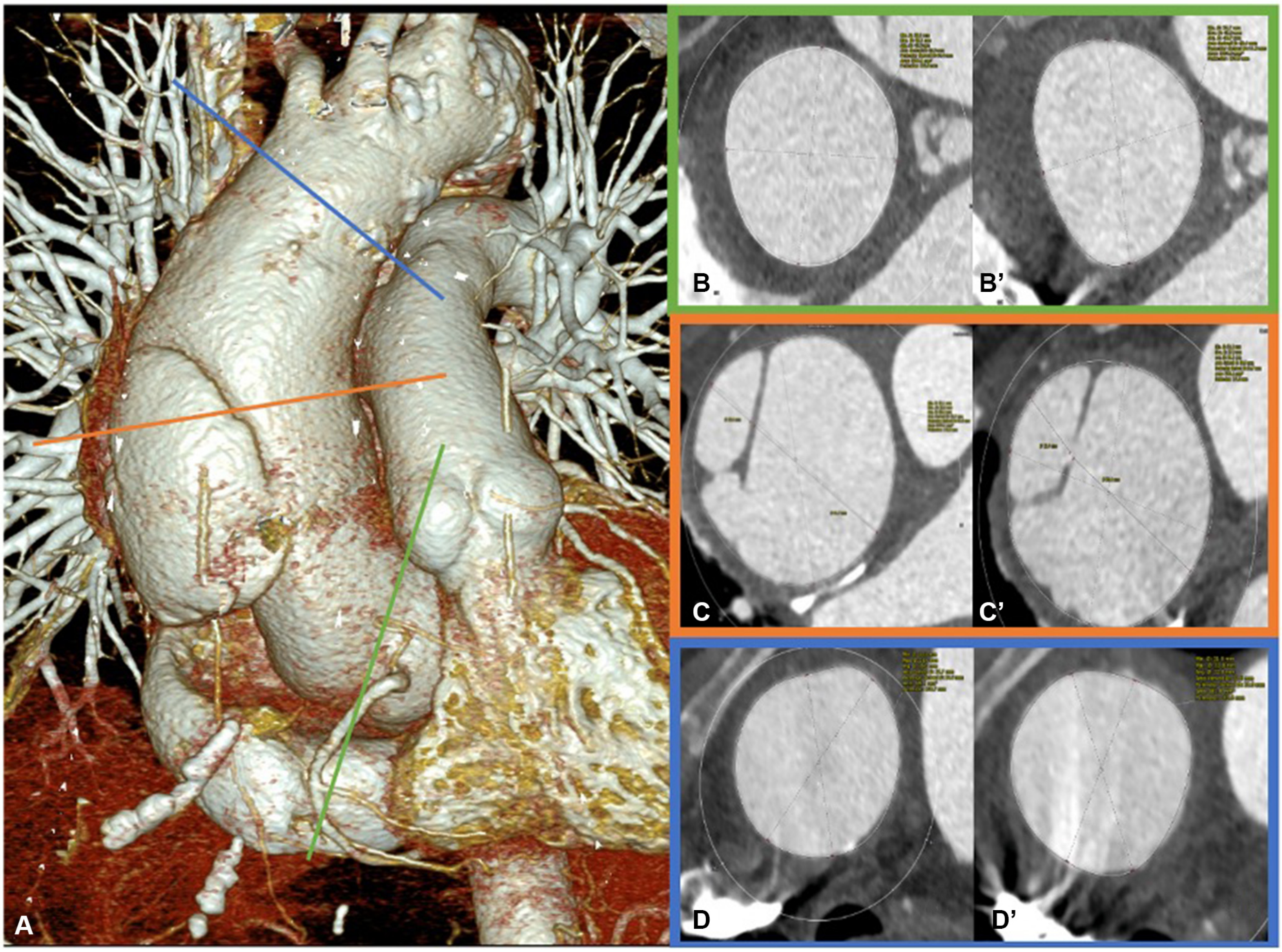

FIGURE E1. ECG-gated CTA. Three-dimensional volume-rendered reconstruction of a CTA depicting a focal ascending aortic dissection (A) and axial planes of an MPR passing through the proximal (*green line*), mid- (*orange line*), and distal (*blue line*) ascending aorta. ECG gating improves image quality and correct measuring for device sizing, as well as highlighting aortic morphology throughout the cardiac cycle. On the left, measurements are taken in the systolic (B, C, D) and diastolic (B’, C’, D’) phases, corresponding to 45% and 70% of the R’R interval. *ECG*, Electrocardiogram; *CTA*, computed tomography angiography; *MPR*, multiplanar reconstruction.