JACC: CARDIOVASCULAR IMAGING VOL. ■, NO. ■, 2019

PUBLISHED BY ELSEVIER

iREVIEW

STATE-OF-THE-ART PAPER

Optimizing Cardiac CT Protocols for Comprehensive Acquisition Prior to Percutaneous MV and TV Repair/Replacement

Todd C. Pulerwitz, MD,[a,b,*] Omar K. Khalique, MD,[a,b,*] Jay Leb, MD,[b] Rebecca T. Hahn, MD,[a] Tamim M. Nazif, MD,[a] Martin B. Leon, MD,[a] Isaac George, MD,[c] Torsten P. Vahl, MD,[a] Belinda D'Souza, MD,[b] Vinayak N. Bapat, MD,[c] Shifali Dumeer, MD,[b] Susheel K. Kodali, MD,[a] Andrew J. Einstein, MD, PhD[a,b]

ABSTRACT

Clinical trials of transcatheter mitral valve and tricuspid valve repair and replacement devices have begun in earnest, with the ultimate goal of providing definitive, nonsurgical treatment for the millions of patients with severe, symptomatic regurgitation, many of whom are too high risk or inoperable for a surgical approach. Computed tomography (CT) angiography offers the potential for detailed anatomic assessment in this patient population, but its optimal implementation for patients with mitral and tricuspid disease requires patient-centered protocol specification reflecting the goal of the scan, an understanding of complex anatomy and pathophysiology, and particulars of CT scanner capabilities. In this paper, the need for new interventional approaches to mitral and tricuspid valve disease is discussed, followed by a detailed review of how to perform a high-quality CT angiography examination, taking into consideration scanner- and patient-specific variables when preparing a pre-mitral or tricuspid protocol. The many possible clinical challenges affecting the performance of cardiac and vascular CT angiography for pre-procedure mitral and tricuspid repair/replacement are reviewed and specific tips, trouble-shooting approaches, and recommendations are provided for how to conduct the best-quality study, be it at an experienced imaging center with the most advanced scanner or at a novice center using an earlier generation CT platform. (J Am Coll Cardiol Img 2019;■:■–■) © 2019 by the American College of Cardiology Foundation.

From the [a]Division of Cardiology, Department of Medicine, Columbia University Irving Medical Center/New York-Presbyterian Hospital, New York, New York; [b]Department of Radiology, Columbia University Irving Medical Center/New York-Presbyterian Hospital, New York, New York; and the [c]Department of Surgery, Columbia University Irving Medical Center/New York-Presbyterian Hospital, New York, New York. *Drs. Pulerwitz and Khalique have contributed equally to this manuscript. Dr. Khalique has received consulting fees from Edwards Lifesciences, Cephea Valves, Jenavalve, and Boston Scientific; and is a member of a Core Lab that holds contracts with Edwards Lifesciences, but receives no direct compensation. Dr. Hahn has received Core Lab contracts with Edwards Lifesciences, but receives no direct compensation; and is a speaker for Philips Healthcare, St. Jude's Medical, and Boston Scientific. Dr. Nazif has received consulting fees from Edwards Lifesciences, Medtronic, and Boston Scientific. Dr. Leon is a nonpaid member of the Scientific Advisory Board of Edwards Lifesciences. Dr. George has received consulting fees from Edwards Lifesciences, Medtronic, W. L. Gore, MITRx, and Mitre Medical; and is a speaker for Edwards Lifesciences, Medtronic, and Boston Scientific. Dr. Vahl has received consulting fees from Edwards Lifesciences and JenaValve Technology. Dr. Bapat has received consulting fees from Edwards Lifesciences, Medtronic, and Abbott. Dr. Kodali has received consulting fees from Edwards Lifesciences, Abbott Vascular, Meril Lifesciences, Claret Medical, Admedus; is on the Advisory Board of Dura Biotech, Thubrikar Aortic Valve, Inc., and Biotrace Medical has received honoraria from Abbott Vascular, Meril Lifesciences, Claret Medical, and Admedus; and has equity in Thubrikar Aortic Valve Inc., Dura Biotech, and Biotrace Medical. Dr. Einstein has received research grants to Columbia University from Canon Medical Systems and Roche Diagnostics; and has served as a consultant to GE Healthcare. All other authors have reported that they have no relationships relevant to the contents of this paper to disclose.

Manuscript received May 30, 2018; revised manuscript received January 14, 2019, accepted January 22, 2019.

ISSN 1936-878X/$36.00 https://doi.org/10.1016/j.jcmg.2019.01.041

ABBREVIATIONS AND ACRONYMS

CT = computed tomography

CTA = computed tomography angiography

ECG = electrocardiogram

HU = Hounsfield units

IV = intravenous

LVOT = left ventricular outflow tract

MV = mitral valve

ROI = region of interest

TAVR = transcatheter aortic valve replacement

TMVR = transcatheter mitral valve repair/replacement

TTVR = transcatheter tricuspid valve repair/replacement

TV = tricuspid valve

Percutaneous and surgical interventions for structural heart disease are burgeoning. Since the first Food and Drug Administration approval of a percutaneous prosthetic aortic valve in 2011, more than 80,000 commercial transcatheter aortic valve replacement (TAVR) procedures have been performed in the United States. Although treatment with TAVR will become increasingly common, moderate or severe mitral valve (MV) disease, most notably mitral regurgitation, remains the most prevalent type of valve disease, surpassing aortic stenosis prevalence by greater margins with each decade of life (1,2). Computed tomography angiography (CTA), both cardiac and vascular, has become the standard imaging modality to assess suitability for percutaneous transcatheter MV repair/replacement (TMVR) and transcatheter tricuspid valve (TV) repair/replacement (TTVR) (3-5). This manuscript provides the background and technical details for imagers of all backgrounds to be able to direct and perform high-quality cardiac and vascular computed tomography (CT) imaging for MV and TV assessment for percutaneous intervention planning. We begin by reviewing the new transcatheter approaches to severe MV and TV disease, followed by a detailed review of how to perform a high-quality CTA examination, taking into consideration scanner- and patient-specific variables and trouble-shooting common challenges and providing specific tips for MV and TV CT protocols.

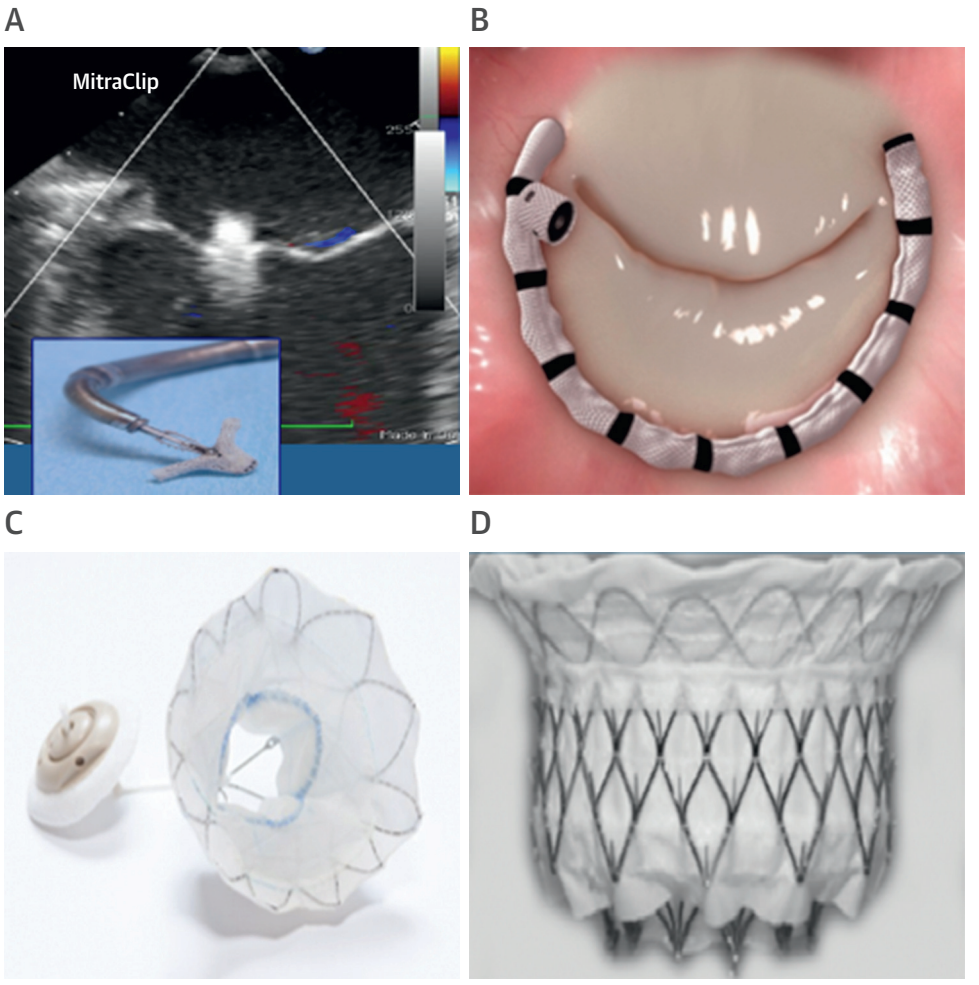
BASIC PRINCIPLES: MITRAL AND TRICUSPID DISEASE AND CURRENT PERCUTANEOUS VALVE TECHNOLOGIES

MV DISEASE. MV disease is the most common valve disease in the United States. Almost 1 in 10 patients 75 years and older in the United States will have moderate or severe mitral regurgitation (1). Only a small proportion of patients with moderate or severe regurgitation undergo surgical repair/replacement (6). The percutaneous Mitra-Clip (Abbott Vascular, Abbott Park, Illinois) is the only commercially approved technology for severe native valve regurgitation in the United States, and is currently approved for use in symptomatic secondary mitral regurgitation in high-risk or inoperable patients only (7). In Europe, the Cardioband (Edwards Lifesciences, Irvine, California) and Mitralign (Mitralign, Inc., Tewksbury, Massachusetts) devices hold a CE mark. Therefore, there is significant potential to expand percutaneous TMVR into a much larger population (estimated as up to 5 million patients in the United States by 2030). Additionally, patients with degenerative mitral stenosis (constituting up to 60% of patients older than 80 years with mitral stenosis) are at significant surgical risk, especially in the setting of numerous comorbidities (8-13). Indeed, at least 50 percutaneous MV repair or replacement platforms are currently in development (**Figure 1**). There are approximately 15 MV device trials ongoing in the United States and Europe. The recent findings of the COAPT trial, which demonstrated that the Mitra-Clip can reduce hospitalization and all-cause mortality and improve exercise tolerance and quality of life in patients with heart failure with moderate to severe or severe functional mitral regurgitation compared with medical management alone has only increased excitement (14).

TV DISEASE. TV disease affects many patients in the United States, where an estimated 1.6 million individuals have moderate or severe regurgitation but only about 8,000 undergo repair or replacement annually (15). Tricuspid regurgitation is known to be associated with significant mortality (16). Therefore, there may be many patients who may benefit from repair/replacement who are not offered surgery (up to 25% significant morbidity or mortality), but for whom a less invasive, percutaneous approach could be highly beneficial (17). Currently there are 7 TV device trials under way in North America and Europe with many more devices in development (**Figure 2**) (18-21).

BASIC VALVULAR ANATOMIC AND PATHOPHYSIOLOGIC DIFFERENCES. Expert knowledge of the MV and TV apparatuses is necessary to fully comprehend the design and clinical challenges of percutaneous TMVR and TTVR devices. The main challenges for TMVR are selection of the optimal approach to placement (most commonly direct transapical, with developing transvenous and transseptal therapies), avoidance of damaging subvalvular structures and the conduction system, close proximity to the aortic valve/annulus, and avoidance of creating significant left ventricular outflow tract (LVOT) obstruction (**Central Illustration, Figure 3**). Several challenges exist for successful TTVR. These include the angulation of the annulus in reference to the inferior vena cava and superior vena cava, which complicates the ability to obtain a needed coaxial deployment of the valve system; the large TV annulus, which complicates device fixation; and slow right-side blood flow and associated risk of thrombus formation. Additional challenges include close proximity of the right coronary artery and coronary sinus and the trabeculated and thin architecture of the right

FIGURE 1 **Transcatheter MV Repair/Replacement Examples**



Four major MV platforms. **(A)** Edge-to-edge clip/repair: MitraClip transcatheter MV (Abbott Vascular, Abbott Park, Illinois). **(B)** Mitral repair annuloplasty: Cardioband transcatheter mitral repair annuloplasty system (Edwards Lifesciences, Irvine, California). **(C)** MV replacement: Tendyne Bioprosthetic MV replacement compromised of a symmetrical trileaflet porcine pericardial valve with adjustable tether and apical fixation/sealing pad (Abbott Vascular). **(D)** MV replacement system: Twelve Intrepid MV Replacement system housing a tri-leaflet bovine pericardium valve within a self-expandable nitinol outer stent (Medtronic, Minneapolis Minnesota). MV = mitral valve.

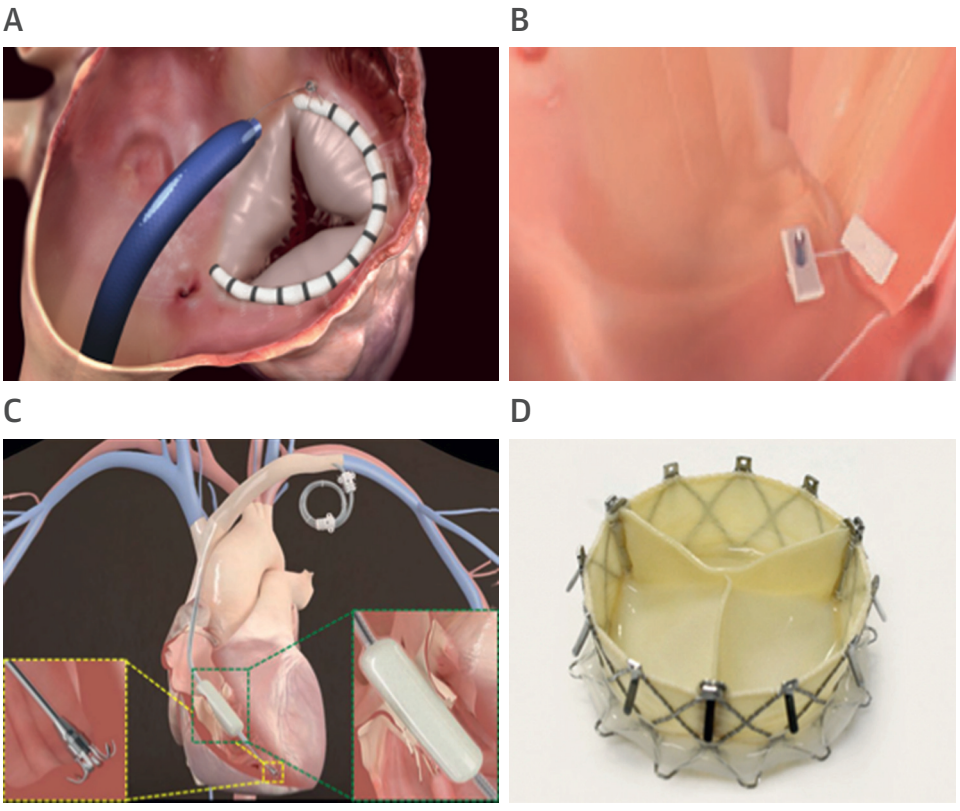
ventricle, all of which potentially complicate access and device deployment/fixation (**Central Illustration**) (17,22). Given all these extremely important anatomic variables that require detailed measurements for a specific percutaneous therapy, CTA is critical in patient assessment and therefore, image quality is of the utmost importance.

CHALLENGES IN SCAN PROTOCOL DEVELOPMENT

One of the developing challenges will be the need to anatomically screen a single patient for multiple devices for a given valve using CTA, without knowing which device will be used before protocoling the scan. Given that each device has specific anatomic considerations and interactions, a broad protocol needs to be developed at each institution to cover their potential devices. Although the current document covers considerations for cardiac CTA acquisition for planning of currently available and studied devices, adjustments need to be made to protocols as devices and access pathways evolve.

TMVR. Optimal left-sided opacification is necessary in all cases. If device and access path are unknown,

FIGURE 2 Transcatheter TV Repair/Replacement Device Examples



Four transcatheter TV repair/replacement technologies by approach. **(A)** TV repair annuloplasty: Cardioband TV Reconstruction System, a transfemoral implant that reduces the tricuspid annulus to minimize regurgitation (Edwards Lifesciences, Irvine, California). **(B)** TV annuloplication: Trialign System, sutures are placed into the tricuspid annulus, cinching it with goal of bicuspidization of the TV (Mitralign, Inc., Tewksbury, Massachusetts). **(C)** TV spacer- Forma: inflated balloon sits across the TV decreasing the regurgitant orifice area (Edwards Lifesciences). **(D)** TV replacement: GATE, a series of atrial winglets and ventricular graspers that provide radial fixation of the prosthesis into the tricuspid annulus and apparatus (NaviGate valves; NaviGate Cardiac Structures, Lake Forest, California). TV = tricuspid valve.

one may need to obtain peripheral arterial and venous phase examinations. If transseptal planning is a possibility, at least a small amount of right-sided opacification is ideal for interatrial septum visualization.

TTVR. Optimal and smooth right-sided opacification is necessary in all cases. In most cases, a peripheral venous phase including the jugular veins is needed. If device is unknown, one may need adequate left-sided and right coronary opacification to assess potential tricuspid device interaction with the right coronary artery.

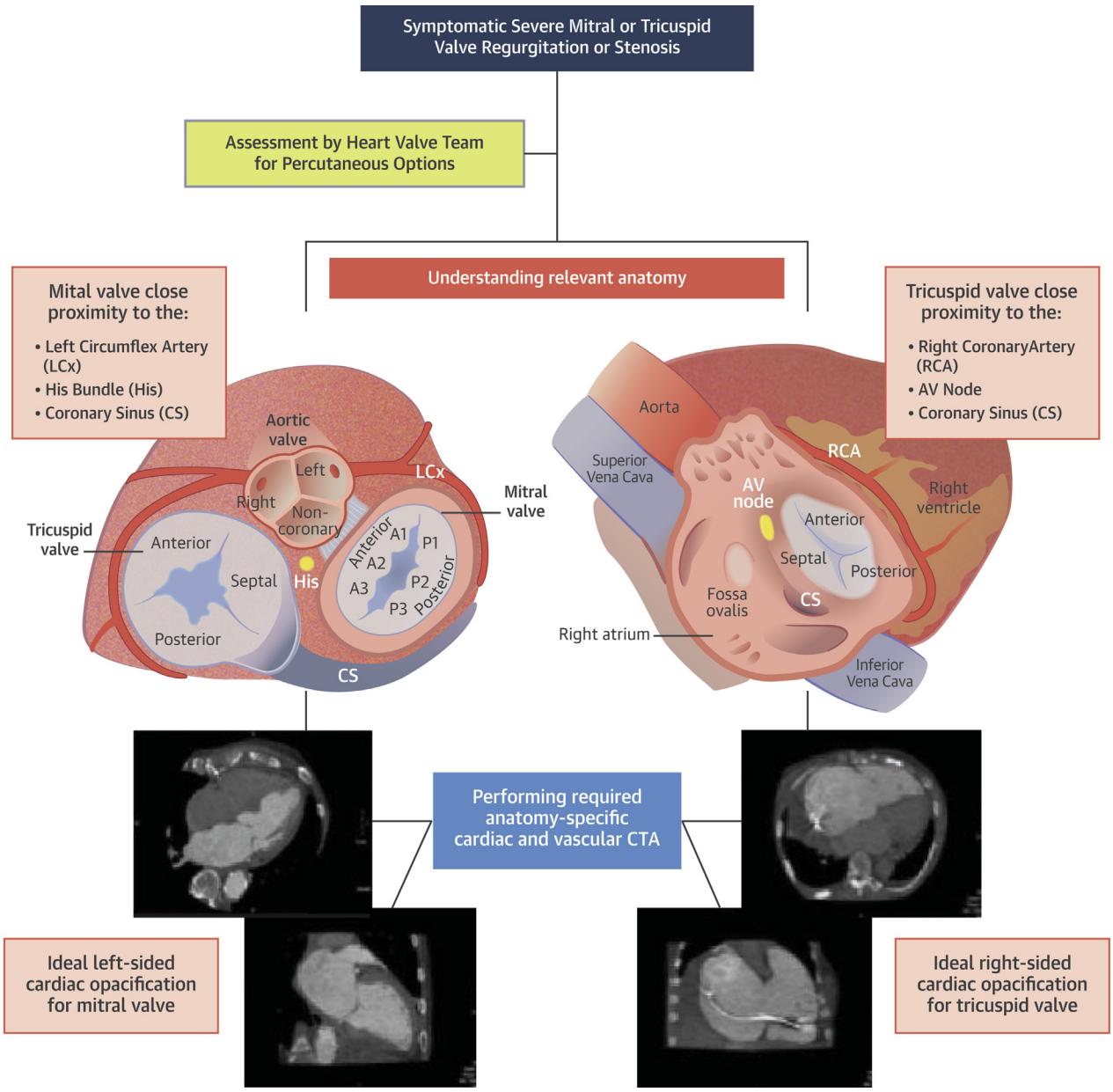
SCANNER FACTORS IMPACTING IMAGING

Several scanner-related factors affect image acquisition.

CRANIOCAUDAL (Z-AXIS) COVERAGE. Frequently for TMVR and TTVR patients, the craniocaudal height of the heart is 14 to 16 cm given the extensive dilation of the atria and ventricles that can occur. Having a more advanced scanner (higher temporal resolution/greater number of detector rows) has advantages for greater craniocaudal coverage and faster acquisition, although a minimum requirement of a 64-detector-row scanner is needed. Shorter craniocaudal coverage, however, results in a longer scanning time and longer breath-hold (problematic for a patient with heart failure symptoms), and increases the likelihood of motion or misregistration artifact.

SCANNER ACQUISITION MODE. A primary goal for pre-TMVR and pre-TTVR CT evaluation is to obtain a high-quality electrocardiogram (ECG)-gated cardiac scan with as close to full cardiac cycle coverage (R-R interval) as possible (23). The mode used by the CT scanner for the cardiac scan can be prospectively

CENTRAL ILLUSTRATION **Clinical Approach to Imaging Evaluation of Patients With Severe, Symptomatic Mitral and Tricuspid Valve Disease Under Consideration for Percutaneous Therapies**

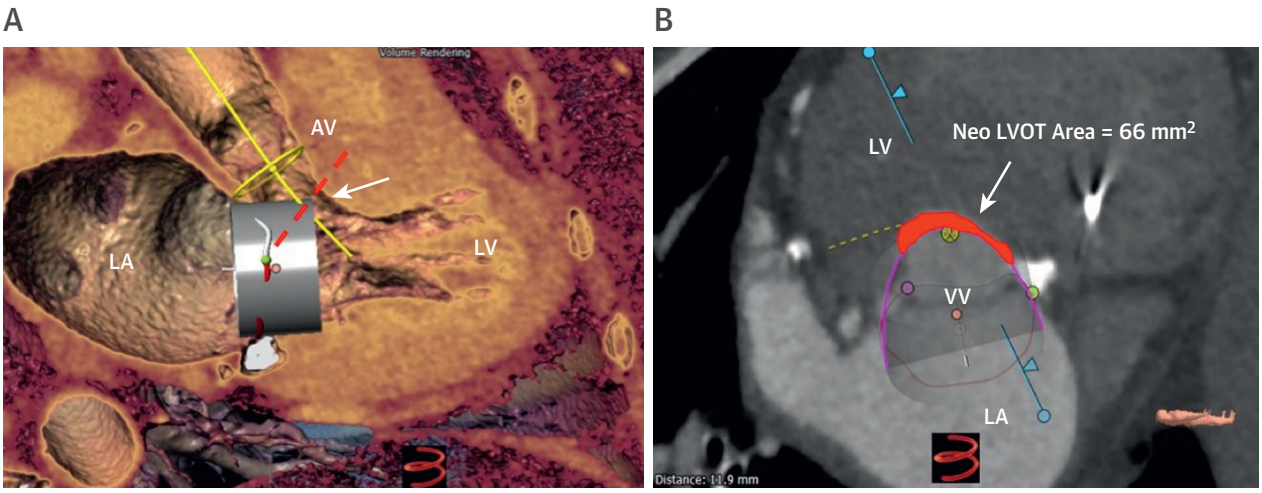


Pulerwitz, T.C. et al. J Am Coll Cardiol Img. 2019;■(■):■–■.

AV = atrioventricular.

triggered axial step-and-shoot, prospectively triggered high-pitch or low-pitch helical, retrospectively gated low-pitch helical scanning, or volume scan mode. High-pitch helical cardiac scanning is only feasible for dual-source scanners, whereas volume scanning (in which the entire heart is covered in a single heartbeat without the need to move the patient table) is only available for extended coverage (256- or 320-detector-row) scanners. Although up to 16 cm of craniocaudal coverage is ample for almost all patients undergoing other cardiac CTA applications, it may be insufficient to cover the entire dilated heart in

FIGURE 3 Pre-Procedural Planning of Projected Neo-LVOT Area



Assessment performed with simulated 29-mm Sapien S3 valve using 3-Mensio software, version 9.1 (Pie Medical, Maastricht, the Netherlands). **(A)** Volume-rendered image of a 3-chamber view with virtual valve implantation of a 29-mm S3 valve **(grey cylinder)** into the mitral position for valve in mitral annular calcification planning is shown. To assess the risk of LVOT obstruction, a simulated neo-LVOT area is performed by scrolling down the centerline from the aorta to the LVOT **(solid yellow line)** to the narrowest portion of LVOT in a mid-systolic phase with virtual valve in place **(dashed red line; white arrow identifying "Neo-LVOT")**. **(B)** Computed tomography angiogram short-axis at the level of the **dashed red line** from **A** shows the "Neo-LVOT" measurement **(solid red shape)** at the maximum protrusion of the transcatheter valve. A "Neo-LVOT" area less than 150 mm^2 or 60% reduction or greater from baseline LVOT area may be associated with elevated LVOT gradients.
AV = aortic valve; LA = left atrium; LV = left ventricle; LVOT = left ventricular outflow tract; VV = virtual valve.

pre-TMVR and pre-TTVR patients. Selection of scan mode should be performed taking into account the scanner's capabilities. Scanner speed and z-axis coverage are 2 critical factors to be considered when designing acquisition protocols. For TMVR and TTVR, an additional scan may be required for anatomic assessment of the peripheral vasculature. The goal for the broad pre-TMVR scan is currently to obtain both arterial and venous anatomy, given that either a transvenous/transseptal or a transfemoral arterial approach may be used, whereas for pre-TTVR it is only to obtain venous anatomy. This vascular scan is performed using a non-ECG-synchronized low- or high-pitch helical scan. For TMVR, if using the same contrast bolus as that used for cardiac scanning, the peripheral vascular arterial scan should be obtained directly after the cardiac scan or if exclusively for transseptal TMVR devices, with a longer interscan delay (65 s), to best assess venous anatomy. For TTVR, it is mandatory to add an interscan delay to enable adequate venous filling.

TABLE 1 Summary of Commercially Available Computed Tomography Scanners

Types of Scanners	Maximal Z-Axis Coverage (cm)	Comments
Single source: standard coverage	3.2–4.0	Lowest recommended coverage for pre-TMVR and TTVR scanning Need 4–6 acquisitions to cover entire heart for prospective ECG-triggered axial mode
Dual source	3.8–5.76	Enhanced temporal resolution Using highest pitch mode cannot acquire entire cardiac cycle or a different portion of the cardiac cycle may occur at the top of the scan versus the bottom
Single source: extended coverage	8.0	Need 2 acquisitions to cover entire heart using prospective ECG-triggered axial mode
Single source: full-volume coverage	16.0	Entire heart typically acquired in 1 acquisition (depends if >16 cm coverage needed) No misregistration/stair-step artifacts Wide z-axis coverage allows for reduction in intravenous contrast volume

Simplified and updated from Khalique et al. (23).
ECG = electrocardiogram; TMVR = transcatheter mitral valve repair/replacement; TTVR = transcatheter tricuspid valve repair/replacement.

DATA COLLIMATION AND IMAGE RECONSTRUCTION. Data should be acquired at the smallest available collimation; this should be no more than 0.625 mm. Cardiac scan reconstruction should use an iterative algorithm if available, with a standard soft tissue kernel at a maximum slice thickness of <1 mm (recommended 0.5 to 0.625 mm) with moderate overlap. A detailed discussion of the types of reconstruction algorithms is beyond the scope of this paper, although advancements in iterative reconstruction have allowed for reduced radiation exposure, higher quality images, and a potential reduction in contrast volume needed (24). The complete R-R interval should be reconstructed by 10% intervals at the minimum, but ideally 5% increments allowing for a 0% to 95% phase dataset (25–28). Cardiac reconstruction field of view for both protocols should include the most anterior structures (as superficial as skin layer for transapical planning). For vascular imaging, it is acceptable to use ≤2-mm thickness reconstructions from the external auditory canal to lesser trochanter for pre-TTVR, and from the diaphragm to lesser trochanter for current pre-TMVR protocols. The transvenous, transseptal approach is the future of TMVR and already used for valve-in-valve TMVR and in that case, vasculature imaging and reconstruction would parallel the pre-TTVR approach.

CT SYSTEMS. Many CT systems can be used for pre-TMVR and TTVR CTA assessment. Table 1 summarizes basic differences of systems with associated clinical implications.

PATIENT PREPARATION FOR OPTIMIZED IMAGING

Ideal preparation (as outlined next) results in obtaining a high-quality CT scan.

HYDRATION. Patients should come well hydrated to allow for easier intravenous (IV) placement, lower heart rates, and reduced likelihood of contrast-induced nephropathy. Patients should typically hold their diuretic agents on the morning of the study and come with a bottle of water to drink while awaiting the CT scan.

IV ACCESS. Eighteen-gauge IV access is recommended, although a 20-gauge is typically adequate when using a 4 ml/s injection rate (although some have recommended as high as 5 ml/s). Right (rather than left) antecubital vein selection is preferred to decrease possible streak artifact caused from contrast crossing the mid-line.

PRE-MEDICATION. Patients with severe MV or TV dysfunction generally tolerate a low-dose negative chronotropic/inotropic agent, and thus use of low-dose beta-blocker (we give metoprolol tartrate 5 mg IV, up to 2 doses) or diltiazem (10 mg IV) when beta-blocker is contraindicated, ideally should take place especially for patients with heart rates above 100 beats/min.

ECG PLACEMENT. Obtaining a high-quality ECG signal, while basic, significantly affects scan quality. Attention should be paid that all cardiac beats are accurately "tracked" by the ECG monitor during a few full breath-holds because this patient population frequently has ectopy and/or a ventricular paced rhythm, in addition to an underlying cardiomyopathy, which can result in very low voltage QRS complexes. If the QRS vector on the ECG signal is not being picked up by the tracking monitor, we change from the default ECG lead tracked (e.g., from lead II to III, or vice versa), and/or move away from standard lead placement (e.g., move "left lower extremity" lead to a more midline sternal border position, or move an upper extremity lead to its corresponding upper sternal border). In the absence of good detection of QRS complexes, a beat or 2 could be "dropped" during the scan, preventing appropriate ECG triggering or gating.

SPECIFICATION OF SCAN PROTOCOLS

SCOUT. For both mitral and TV protocols, a standard anteroposterior and lateral scout is conducted. For the mitral protocol, the scout should extend from clavicle to lesser trochanter, whereas for tricuspid, from external auditory canal to lesser trochanter. The tricuspid vascular assessment needs to include internal jugular veins, whereas the mitral protocol only requires assessment of vasculature caudal to the cardiac scan.

CALCIUM SCORING. Following the initial scout imaging, we perform a noncontrast calcium scoring scan covering from about 1 cm inferior to the carina to below the apex of the heart. For some TMVR research protocols, a standard calcium score is requested. Otherwise we perform this as a "CT scout," a preplanning tool for potentially large heart acquisition, with a "low dose" ECG-gated scan with low tube potential (e.g., 100 kilovolt [peak] [kV(p)]) and current of 100 mA or less. This enables a more detailed and accurate localization of the heart than the standard scout, at the expense of very little additional radiation exposure and in fact a highly probable reduction

TABLE 2 CTA Protocol for Pre-TMVR Evaluation

	BMI* (kg/m^2)	kV	mA†	Contrast Dose (ml)	Rate (ml/s)	Saline Flush (ml)	Scan Delay (s)
60-70 ml protocol‡	≤25	100	Optimize	60-70	4-4.5	30-40	5
70-80 ml protocol‡	25-30	100	Optimize	70-80	4.5-5	40	5
80-90 ml protocol‡	≥30	120	Optimize	80-90	5	40	5

Scan trigger value 150 HU (though for Toshiba Aquilion One family voice trigger should be 30 HU below scan trigger value). *For patients with BMI ≤25 kg/m^2 and of younger age, for which radiation exposure reduction is desired, can consider adjusting kV to 70-80. †Optimize mA when possible recommend using automatic mA or manual selection by experienced operator. ‡Recommend using upper end of range of contrast dose for earlier generation scanners.

BMI = body mass index; CTA = computed tomography angiography; HU, Hounsfield units; other abbreviations as in Table 1.

in total study radiation exposure (by reducing scan length) (29).

CONTRAST INJECTION APPROACH. Although high-quality TMVR/TTVR scans can be obtained with a test-bolus technique (30), most centers prefer a bolus tracking strategy for its simplicity, reproducibility, and reduction in additional contrast injection (31). For TMVR, the region of interest (ROI) should be placed in the descending thoracic or ascending aorta (depending on institutional preference). Care should be made to avoid selecting an area with severe aortic calcification or otherwise manually triggering when a threshold opacification in Hounsfield units (HU) has been met.

In contrast, for the TV protocol for patients requiring right-sided opacification only, placing the ROI in the middle of the right ventricular chamber rather than too apically or laterally, is recommended to avoid getting "lost" in the heavy trabeculations of the right ventricle, which could prevent reaching the threshold HU and thereby scan trigger. On the contrary, placing the ROI too close to the TV may result in prematurely reaching the trigger value, before allowing for adequate mixing to occur between the right atrium and ventricle.

For those scanners that allow for repositioning of the selected ROI while "tracking" the contrast, one's hand should be on the scanner console's mouse, ready to immediately readjust the ROI in case the trigger location is no longer optimally located. Otherwise one should always be ready to manually trigger the scan.

CONTRAST PROTOCOL. At minimum, a dual-syringe (biphasic for contrast and saline flush) injector system should be used. An injection system with dual-flow injection capability, enabling a contrast and saline mixture, has advantages and is required for certain tricuspid protocols (32). A standard contrast agent, with an iodine concentration of 270 to 370 mgI/ml should be used. Protocols described here are based on a concentration of 350 mgI/ml (although if using lower concentration, one will need to adjust contrast injection by increasing contrast flow rate to compensate). The contrast should be injected at an injection rate of 4 to 5 ml/s for a total of 60 to 100 ml of contrast. For most of our scans, we use a tube potential of 100 kV. By definition, the duration of the cardiac cycle (i.e., R-R interval, in milliseconds) multiplied by the heart rate (in beats per minute) equals 60,000; one can use this equation to determine a reasonable x-ray exposure time to cover the entire R-R interval. Specifically for axial scanning, maintaining adequate "padding" on each side of the R-R interval to allow for complete cardiac cycle reconstruction is necessary. Our default x-ray exposure time for the cardiac scan is 1,200 ms (for a heart

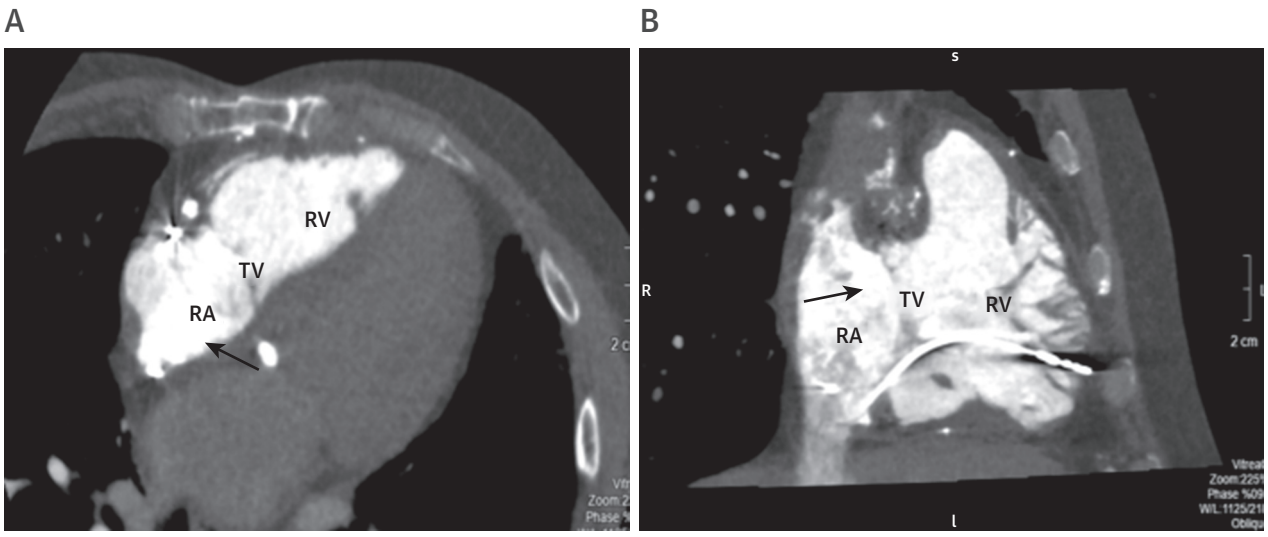
TABLE 3 CTA Protocol for Pre-TTVR Evaluation

	BMI (kg/m^2)	kV	mA*	Phase #1 Injection (Contrast/Saline % in ml/s)	Phase #2 injection (Contrast/Saline % in ml/s)	Phase #3 Injection (Saline in ml at ml/s)	Trigger (HU) and Scan Delay (s)
61 ml protocol	<30	100†	Optimize	60/40 at 4 for 15 s	25/75 at 4 for 25 s	20 at 4	Trigger: 180 Scan delay: 5
70 ml protocol‡	<30	100	Optimize	60/40 at 4 for 22 s	25/75 at 4 for 16 s	20 at 4	Trigger: 180 Scan delay: 5
75 ml protocol	≥30	120	Optimize	60/40 at 4.5 for 20 s	25/75 at 4.5 for 19 s	20 at 4	Trigger: 180 Scan delay: 5

If using the Toshiba Aquilion One family, trigger values for voice 30 HU below scan trigger value. *When possible recommend using automatic mA selection. Alternatively, optimization of mA may be selected manually by an experienced operator. †For patients with BMI ≤25 kg/m^2 and of younger age that radiation exposure reduction desired, can consider adjusting tube potential to 70 or 80 kV (depending on scanner; 70 kV using Siemens Force with maximum tube current selection up to 1,300 mA). ‡Use 70 ml protocol for earlier generation scanner that requires longer cardiac scan to cover up to 16 cm craniocaudal coverage.

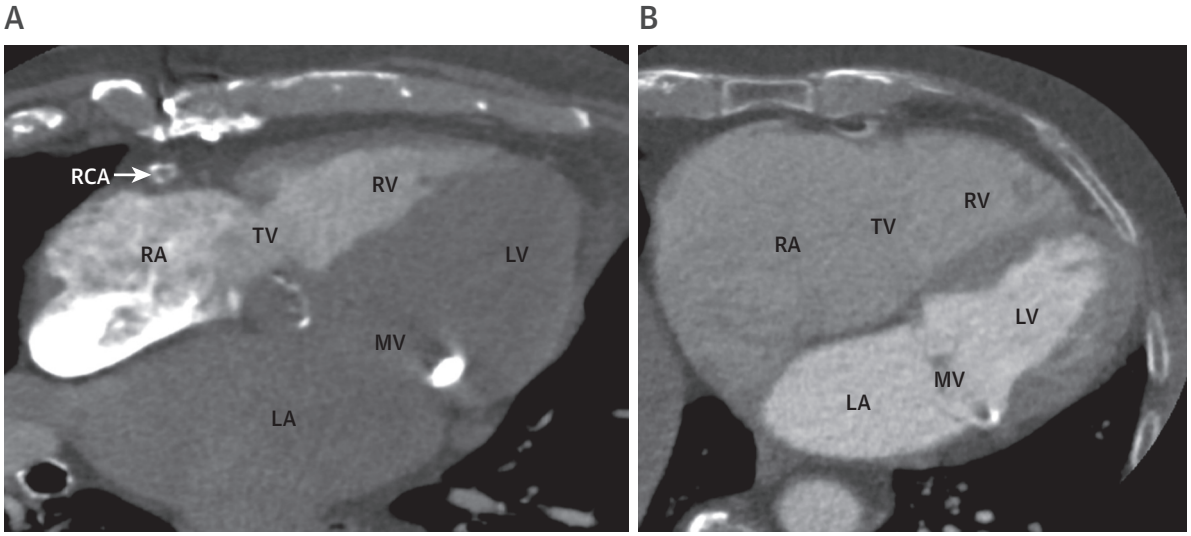
Abbreviations as in Tables 1 and 2.

FIGURE 4 Examples of Suboptimal Right-Sided Opacification for Pre-Transcatheter Tricuspid Valve Repair/Replacement Computed Tomography Angiography Studies



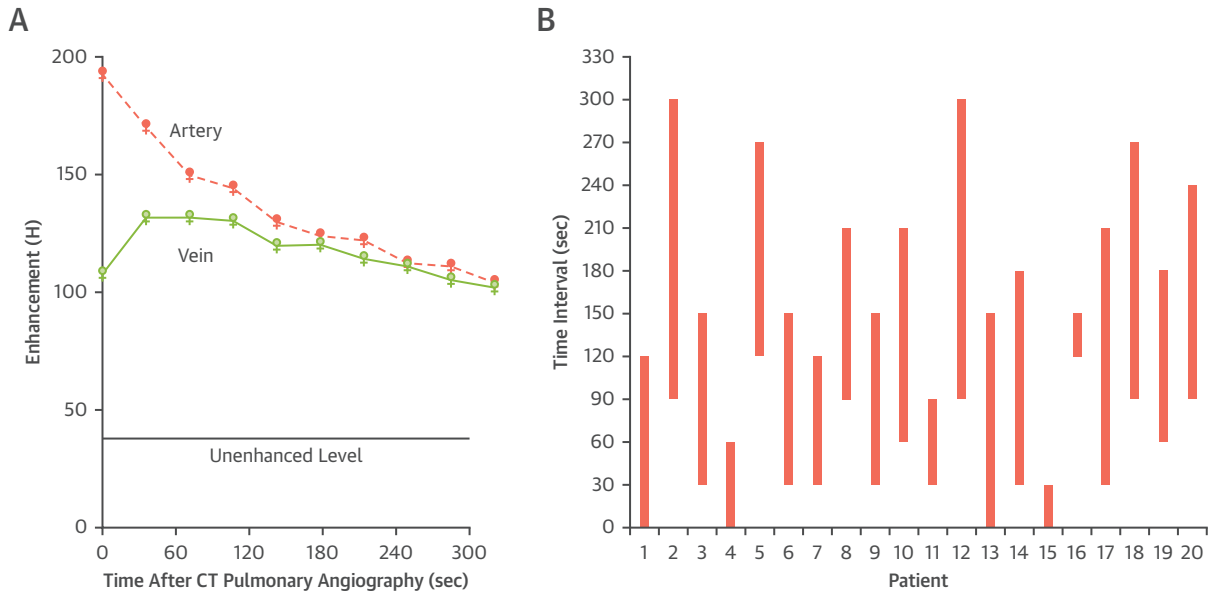
Four-chamber **(A)** and 2-chamber **(B)** views. While using appropriately diluted contrast, premature triggering still occurs when inadequate post-threshold trigger delay is set to allow for ideal homogenous mixing of right-sided contrast. In these 2 images, significant streak artifact is seen in the right heart **(arrow)**. RA = right atrium; RV = right ventricle; other abbreviation as in Figure 2.

FIGURE 5 Pre-Transcatheter Tricuspid Valve Repair/Replacement Computed Tomography Angiography Images Demonstrating Suboptimal Opacification



(A) Nondiluted contrast in addition to lack of necessary 5-second delay for RA/RV mixing, resulting in premature and suboptimal triggering (from region of interest placed in the RV) and **(B)** late trigger off the descending thoracic aorta without using prolonged, diluted contrast injection resulting in suboptimal right-sided contrast. RCA = right coronary artery; other abbreviations as in Figures 1, 2, 3, and 4.

FIGURE 6 Variable Contrast Enhancement of Common Femoral Vein Based on Time Delay from First Chest Scan

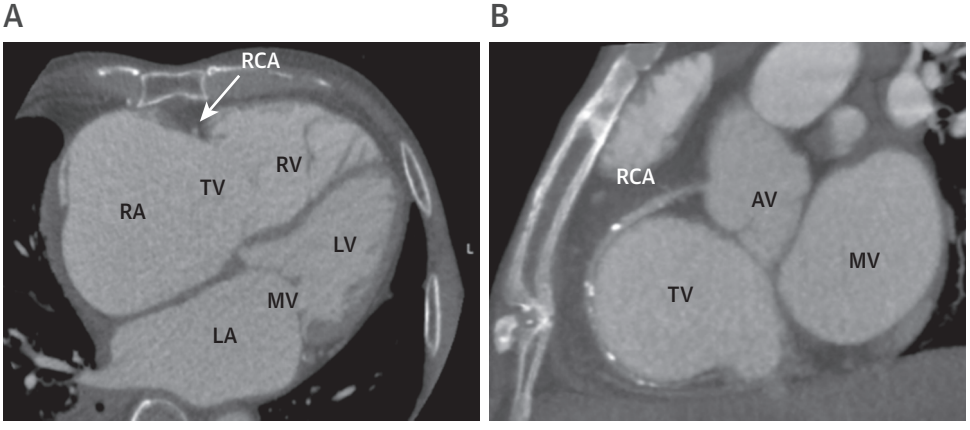


(A) Time-density curve of common femoral artery and vein after completion of CT pulmonary angiography in 1 patient. Density measurement at time T_0 was obtained immediately after CT pulmonary angiography and at 30-s intervals for 5 min. Venous peak enhancement occurs after arterial and is maintained from 30 to 90 s, and **(B)** for each patient during which contrast enhancement of common femoral vein remained within 90% of peak value attained. At 120 s from CT pulmonary angiogram, 85% of patients were within 90% of their peak enhancement. CT = computed tomography.

rate 60 beats/min, corresponding to an R-R interval of 60,000/60 = 1,000 ms, with additional padding to allow for modest heart rate variability). We increase or decrease this exposure time based on heart rate/variability.

Mitral protocol. In TMVR, bolus tracking with a trigger value approximately 100 HU above baseline is used. Because of the additional time necessary for adequate mixing of contrast in the left ventricle to reach a steady state, we recommend an added delay of 5

FIGURE 7 Images Demonstrating Appropriate Left- and Right-Sided Opacification for Pre-Transcatheter Tricuspid Valve Repair/Replacement Cardioband Computed Tomography Angiography Study



(A and B) Scan using prolonged, triphasic, diluted contrast injection protocol to adequately opacify both right coronary artery and right-sided structures. Abbreviations as in Figures 1, 2, 3, 4, and 5.

TABLE 4 How to Avoid Basic Pitfalls: Commonly Encountered Scenarios That Increase Chance of Suboptimal Imaging With Suggested Approach to Prevent Errors

Pitfall	Dos	Don'ts
Early triggering	Triggering off appropriate anatomy (right-sided or left-sided) Add adequate delay to allow for homogenicity of contrast	Not confirming correct anatomy to trigger off Forgetting to add appropriate delay to scan so that contrast mixing occurs
Late triggering	Trigger off correct anatomy Start monitoring correctly Correct scan delay Appropriate trigger thresholds	Not confirming correct anatomy to trigger off Commencing monitoring late Adding too much scan delay Setting threshold too high (especially when using diluted contrast)
Inadequate FOV coverage	Use advanced scout technique to more accurately assess FOV given expected dilated cardiac chambers	Using only standard scout images to guess what correct FOV should be
Poor opacification	Correct trigger timing Correct dilution of contrast Adequate flow rate (increase contrast flow rate especially for patient with higher BMI)	Incorrect trigger location/delay Overdilution of contrast Inadequate flow rate for large patient
Loss of ECG gating	Adequately prepare chest including extra gel and tape for ECG leads Changing of selected lead channel or moving ECG tab closer to heart and over boney structures to correct low voltage/intermittently paced rhythm or PVCs with dropped beats	Inadequate ECG contact resulting in high lead impedance Proceed with scan without high-quality ECG or with frequent dropped beats
Triggering off wrong location	Make certain supervising physician present if possible to remind CT technologist of where to trigger from	Not review individual scan protocol and proceed as "standard" CT especially if protocol infrequently done at institution
Wrong monitoring/scan delay	Review protocol goals as setting up scan to make certain monitoring and scan delay are set correctly	Proceed as "standard" scan without confirming appropriate delay settings
Too much contrast	Preferred method is with single contrast bolus allowing for cardiac immediately followed by second scan Diluting contrast for tricuspid reduces total contrast volume used Total contrast requirement affected by type of scanner (recommendations provided in Tables 2 and 3)	Perform 2 separate scans on same day with each using 60–80 ml per scan Forgetting to dilute contrast for tricuspid study
Inadequate dilution with streak artifact	Dilute contrast especially for ideal right-sided opacification (see Table 3)	Not diluting contrast for imaging focusing on right-sided cardiac structures
Arrhythmia/tachycardia	If tachycardic consistently above 100 beats/min, generally give low-dose metoprolol or diltiazem (depending on institutional approach and individual patient safety) to control heart rate If significant fluctuating R-R intervals (although not tachycardic) in setting of atrial fibrillation or other atrial or ventricular arrhythmia, we prolong the scan exposure so that a full R-R can be reconstructed Scanners that use arrhythmia editing should be used	Ignore heart rate without consideration of rate control Not considering adjusting scan exposure Not using arrhythmia editing if scanner has capability

CT = computed tomography; FOV = field of view; PVC = premature ventricular contraction; other abbreviations as in Tables 1 and 2.

seconds once the threshold has been reached, before scanning (Table 2). Although contrast/saline mixtures can be used, generally a protocol with 100% contrast injection followed by saline chaser offers high-quality results with limited variability. All scans are followed by a saline flush. Directly after the cardiac (combined protocol), we perform a nongated (medium-to-high pitch) helical scan of the abdomen and pelvis (from diaphragm to lesser trochanter) using the original contrast injection. To date, most TMVR procedures have been performed transapically, whereas several transfemoral (transvenous or transarterial) devices are under investigation in early feasibility studies. Although several TMVR platforms are investigating venous access with transseptal puncture, one approach to performing TMVR uses retrograde femoral arterial access; as such, obtaining a vascular CTA covering down to the common femoral arteries is necessary. This strategy will still allow for adequate venous vascular assessment, although not ideal venous opacification. A third venous phase scan could be added if necessary with a 65-s delay, although the additional radiation exposure would need to be justified. When it is necessary to reduce the contrast load (e.g., renal impairment, recent contrast exposure), a total of 30 to 40 ml of contrast could be used. The protocol adjustment would require either reducing the injection rate to 3 to 3.5 ml/s of 100% iodinated contrast, or changing to a mixed contrast/saline approach of 75%/25% for 10 to 12 s and reducing the added delay to 2 rather than 5 s (Table 2).

Tricuspid protocol. In TTVR, bolus tracking in the middle of the right ventricular cavity is used. To avoid the higher chance of streak artifact, to decrease possible premature scanning, and to limit total contrast media used, a triphasic injection is recommended, using a mixed contrast/saline approach (Table 3) (33). Additionally, a scan delay of 5 s is added after the threshold is reached (Figures 4 and 5). We use 180 HU as our standard trigger threshold value,

TABLE 5 Common Challenges in Pre-TMVR and TTVR CTA With Possible Solutions

Patient Variable	Challenge	Possible Solutions
Ectopy/atrial fibrillation/ heart rate variability	Increased cardiac motion and likelihood of artifacts For prospective ECG-triggered axial scanning with need for combining slabs (narrow z-axis coverage scanner), can result in misalignment/stairstep artifact	Use vendor-specific arrhythmia detection algorithm and/or post-scan editing (if available) Image with scanner with greater craniocaudal coverage Widen data acquisition window (exposure time) if using prospective ECG-triggering Select lower pitch helical scan with retrospective ECG-gating
Tachycardia	Increased cardiac motion and likelihood of artifacts For prospective ECG-triggering with need for combining slabs (narrow z-axis coverage scanner), may not be possible to acquire different regions of heart (along z-axis) at same time in cardiac cycle	Image on scanner with better temporal resolution to reduce motion artifact Widen data acquisition window with prospective ECG-triggered scanning or prolong duration of high tube current during retrospective ECG-gated lower pitch, helical scanning to allow reconstruction of a greater number of cardiac phases and selection of a couple phases with the best image quality
Low cardiac output	For bolus-tracking, scanner may time-out because of large time interval before trigger threshold occurs exacerbated by severe regurgitant lesion (although pertinent for both pre-TMVR and TTVR patients, higher probability for pre-TMVR patient) For vascular scan, risk of scan outrunning contrast bolus for pre-TMVR or insufficient time to fully opacify venous structures (for pre-TTVR cases)	Provide adequate flush to push contrast through Delay time interval before start of bolus-tracking to prevent timing out (for TMVR protocol) Manually trigger scan when left ventricle (for TMVR) or right ventricle (for TTVR) visually opacified
High cardiac output	Risk of contrast bolus outrunning scan (rarely a problem)	Reduce triggering threshold with bolus tracking to start scanning earlier Reduce contrast injection rate to prolong contrast injection (if low image/noise ratio allows) Dilute contrast with contrast/saline mixture (e.g., 75%/25% if capable injector) to prolong contrast injection time
Severe valvular regurgitation	For bolus-tracking, scanner may time-out because of large time interval before threshold reached (although pertinent for both isolated severe mitral and tricuspid regurgitation, a pre-TMVR patient with combined severe tricuspid and mitral regurgitation in series, higher risk of time-out) Streak-artifact or nonhomogenous opacification of cardiac chambers	Further delay time interval before start of bolus tracking to prevent timing out Add scan delay from when trigger value reached and cardiac scan initiated (we add 5 s for both of our protocols) Dilute contrast with contrast/saline mixture (e.g., our pre-TTVR uses 2 different mixtures)
Large body habitus	Increased image/noise ratio	Increase tube current (mA)* Increase tube potential (kVp)* Increase contrast injection rate (see specific protocol recommendations)
Poor renal function	Risk of contrast-induced nephropathy	Lower total iodine administered, generally by decreasing total contrast volume Consider performing cardiac and vascular scans on different days (although necessary in rare situations) in concert with individual injection day contrast volume reduction Perform noncontrast assessment and/or consider alternative imaging modalities

Frequently encountered patient variables (i.e., low cardiac output, severe valvular heart disease, arrhythmias, severe renal impairment), potential problem, and recommendations/tips to maximize image quality while limiting patient risk. *Increasing tube current results in a linear increase in radiation exposure. Increasing peak tube potential results in a more-than-linear increase in radiation exposure. Adapted with permission from Khalique et al. (23).

Abbreviations as in Tables 1 and 2.

although it should be set at least 100 HU above pre-contrast baseline Hounsfield value. For TTVR scans, because right-sided cardiac structures are being scanned, a monitoring delay of no more than 2 to 3 s should be used before the initiation of bolus tracking. A venogram is needed as part of the tricuspid protocol, because vascular access possibilities include internal jugular, subclavian, and femoral veins. We perform a nongated (medium-to-high pitch) helical scan of neck, chest, abdomen, and pelvis (from external auditory canal to lesser trochanter). For the venogram scan, an 80-s delay after the cardiac scan is used to allow adequate contrast opacification of the required venous structures (34). In our experience, peak femoral venous opacification can be quite variable and an 80-s delay from the cardiac scan has been selected with goal of obtaining within 90% peak venous opacification (as measured in HU). Yankelevitz et al. (34) nicely demonstrated the extreme variability of common femoral vein opacification in patients undergoing a pulmonary embolism CTA combined with lower extremity venogram using the same contrast injection (**Figures 6A and 6B**). In situations of renal impairment or a desire to limit contrast volume, a total of 30 to 40 ml contrast at 4 ml/s (**Table 3**) could be used, by slightly adjusting the recommended protocol (eliminating the second 25/75% contrast/saline injection). For annuloplasty devices that will be implanted with proximity to the right coronary artery, the CT protocol should trigger off of the thoracic aorta with reduced scan delay to 2 s, using a faster 4.5 to 5 ml/s flow rate, so as to ensure adequate right coronary and right heart opacification (**Figures 7A and 7B**). For this modification, the delay for the venogram scan should be adjusted to 65 s after cardiac scan.

PITFALLS

Several challenges can arise when performing these specialized scans. Recommended approaches to avoid suboptimal scanning are offered in **Table 4** in a "Do and Don't" format.

PATIENT FACTORS IMPACTING IMAGING

Several patient-specific factors need to be taken into consideration that may modify the particulars of scan protocol specification. These include patient size, heart size, cardiac output, renal function, and heart rate and rhythm.

PATIENT SIZE. Patient size and body habitus affect image quality. As body mass index increases so does image noise, which may need to be overcome by an increase in tube output and, possibly, an increase contrast injection rate (23,35). We recommend a tube potential of 100 kV(p) for most patients, with 120 kV(p) reserved for larger patients, although encourage less than 100 kV(p) as appropriate. Automated tube voltage selection based on the topograms is helpful with this decision-making. We encourage optimizing one's scanner's tube current, up to the maximal current supported by the x-ray tube, before increasing tube potential. This approach maximizes the inherent properties of iodinated contrast, and limits radiation exposure (23).

HEART SIZE. As opposed to normal patient heart size, for which craniocaudal coverage of 10 to 14 cm is typical, the typical pre-TMVR or TTVR patient has significant cardiomegaly, frequently increasing this coverage to 14 to 18 cm. Cardiomegaly needs to be considered when tailoring patient-specific protocols.

CARDIAC OUTPUT. In patients undergoing pre-TMVR or pre-TTVR evaluation, the forward flow output is reduced leading to a delay in time to peak opacification (35). This opacification delay should be reflected in setting the appropriate delay time for the bolus tracking approach.

RENAL FUNCTION. Renal dysfunction is a common comorbidity in the pre-TMVR and pre-TTVR population. Pushing the lower limit of contrast for a diagnostic scan may be attainable with advanced CT scanners (i.e., extended coverage scanners and dual-source systems). These technologies have been demonstrated to provide comprehensive assessment (of cardiac and vascular for pre-TAVR patients) with as little as 20 ml of iodinated contrast media (36). For patients with severe renal insufficiency (chronic kidney disease stage 4 or greater) or heightened clinical concern, protocol adjustments can be considered. For valve-in-valve TMVR patients and patients with severe mitral annular calcification, noncontrast ECG-gated cardiac CT with partial or full R-R interval coverage, reconstructed at thin slices can be considered for valve planning, whereas a noncontrast chest, abdomen, and pelvis CT may be useful for vascular assessment, although a low-contrast volume scan is preferred. For other pre-TMVR patients, a 30 to 40 ml protocol can be used on a high-coverage or dual-source scanner. For pre-TTVR patients, a 30 to 40 ml contrast protocol can be used (see Protocol section).

HEART RATE AND RHYTHM. These patients frequently have faster heart rates or arrhythmias, such as atrial fibrillation. We suggest low-dose metoprolol (or diltiazem for patients with contraindications to beta-blockade) (see Pre-medication section) in stable patients with persistent rates above 100 beats/min. In settings of atrial fibrillation or frequent ectopy, prospective triggering may cause incorrect timing of acquisition or inability to scan (impact of heart rate and rhythm variability reduced in scanners with a greater number of detector rows) and high-pitch prospective helical scanning should be avoided instead considering retrospective, low-pitch approach to maximize overlap. Some vendors provide arrhythmia detection algorithms (that can delay scan and wait for return of regular rhythm) or post-processing ECG editing, which may convert suboptimal datasets into good-quality reconstructed images (37). **Table 5** summarizes commonly encountered clinical scenarios with possible solutions and recommendations.

HIGHLIGHTS

- Clinical trials have begun of numerous transcatheter mitral valve and tricuspid valve repair and replacement devices.
- Cardiac and vascular assessment before transcatheter intervention requires high-quality, anatomy-specific CT angiography protocols.
- The many possible clinical challenges affecting CT angiography are reviewed and specific tips and trouble-shooting approaches provided.
- As this field rapidly advances, so too will the requirement for high-quality CT angiography protocols.

CONCLUSIONS

Cardiac and vascular assessment before transcatheter mitral or TV repair/replacement requires high-quality, anatomy-specific CTA protocols. This necessitates an understanding of basic valvular anatomy and pathophysiology, and an appreciation of differences among CT scanners. It mandates careful attention to patient preparation and patient-specific protocol optimization, reflecting body habitus, heart size, renal function, cardiac output, heart rate, and heart rhythm. Percutaneous treatment approaches to severe mitral and TV disease are being tested and it is likely that some will become realistic treatment options for many patients who are not currently surgical candidates, a number expected to be much greater than the number of TAVRs. During this exciting period in the development of percutaneous therapy for mitral and TV disease, as the clinical leap is made for these treatments to benefit so many patients, understanding how to perform comprehensive, valve-specific CTA protocols will allow each clinical center to provide optimal care to its patient population.

ADDRESS FOR CORRESPONDENCE: Dr. Andrew J. Einstein, Columbia University Medical Center, Department of Medicine, Division of Cardiology, 622 West 168th Street, PH 10-203A, New York, New York 10032. E-mail: andrew.einstein@columbia.edu.

REFERENCES

1. Nkomo VT, Gardin JM, Skelton TN, Gottdiener JS, Scott CG, Enriquez-Sarano M. Burden of valvular heart diseases: a population-based study. Lancet 2006;368:1005–11.

2. Nishimura RA, Vahanian A, Eleid MF, Mack MJ. Mitral valve disease—current management and future challenges. Lancet 2016;387:1324–34.

3. Naoum C, Blanke P, Cavalcante JL, Leipsic J. Cardiac computed tomography and cardiac magnetic resonance in the evaluation of mitral and tricuspid valve disease. Circ Cardiovasc Imaging 2017;10:1–17.

4. Regueiro A, Granada JF, Dagenais F, Rodes-Cabau J. Transcatheter mitral valve replacement: insights from early clinical experience and future challenges. J Am Coll Cardiol 2017;69:2175–92.

5. Blanke P, Naoum C, Webb J, et al. Multimodality imaging in the context of transcatheter mitral valve replacement: establishing consensus among modalities and disciplines. J Am Coll Cardiol Img 2015;8:1191–208.

6. Mirabel M, Lung B, Baron G, et al. What are the characteristics of patients with severe, symptomatic, mitral regurgitation who are denied surgery? Eur Heart J 2007;28:1358–65.

7. Nishimura RA, Otto CM, Bonow RO, et al. 2014 AHA/ACC Guideline for the management of patients with valvular heart disease: executive summary. J Am Coll Cardiol 2014;63:2438–88.

8. Watkins DA, Johnson CO, Colquhoun SM, et al. Global, regional, and national burden of rheumatic heart disease, 1990-2015. N Engl J Med 2017;377:713–22.

9. Lung B, Baron G, Butchart EG, et al. A prospective survey of patients with valvular heart disease in Europe: the Euro Heart Survey on Valvular Heart Disease. Eur Heart J 2003;24:1231–43.

10. Guerrero M, Dvir D, Himbert D, et al. Transcatheter mitral valve replacement in native mitral valve disease with severe mitral annular calcification: results from the First Multicenter Global Registry. J Am Coll Cardiol Intv 2016;9:1361–71.

11. Eleid MF, Cabalka AK, Williams MR, et al. Percutaneous transvenous transseptal transcatheter valve implantation in failed bioprosthetic mitral valves, ring annuloplasty, and severe mitral annular calcification. J Am Coll Cardiol Intv 2016;9:1161–74.

12. Søndergaard L, De Backer O, Franzen OW, et al. First-in-human case of transfemoral CardiAQ mitral valve implantation. Circ Cardiovasc Interv 2015;8:7.

13. Muller DW, Farivar RS, Jansz P, et al. Transcatheter mitral valve replacement for patients with symptomatic mitral regurgitation: a global feasibility trial. J Am Coll Cardiol 2017;69:381–91.

14. Stone GW, Lindenfeld J, Abraham WT, et al. Transcatheter mitral-valve repair in patients with heart failure. N Engl J Med 2018;379:2307–18.

15. Stuge O, Liddicoat J. Emerging opportunities for cardiac surgeons within structural heart disease. J Thorac Cardiovasc Surg 2006;132:1258–61.

16. Nath J, Foster E, Heidenreich PA. Impact of tricuspid regurgitation on long-term survival. J Am Coll Cardiol 2004;43:405–9.

17. Taramasso M, Pozzoli A, Guidotti A, et al. Percutaneous tricuspid valve therapies: the new frontier. Eur Heart J 2017;38:639–47.

18. Rodes-Cabau J, Hahn RT, Latib A, et al. Transcatheter therapies for treating tricuspid regurgitation. J Am Coll Cardiol 2016;67:1829–45.

19. Hahn RT, Meduri CU, Davidson CJ, et al. Early feasibility study of a transcatheter tricuspid valve annuloplasty. J Am Coll Cardiol 2017;69:1795–806.

20. Campelo-Parada F, Perlman G, Philippon F, et al. First-in-man experience of a novel transcatheter repair system for treating severe tricuspid regurgitation. J Am Coll Cardiol 2015;66:2475–83.

21. Perlman G, Praz F, Puri R, et al. Transcatheter tricuspid valve repair with a new transcatheter coaptation system for the treatment of severe tricuspid regurgitation: 1-year clinical and echocardiographic results. J Am Coll Cardiol Intv 2017;10:1994–2003.

22. Ong K, Yu G, Jue J. Prevalence and spectrum of conditions associated with severe tricuspid regurgitation. Echocardiography 2014;31:558–62.

23. Khalique OK, Pulerwitz TC, Halliburton SS, et al. Practical considerations for optimizing cardiac computed tomography protocols for comprehensive acquisition prior to transcatheter aortic valve replacement. J Cardiovasc Comput Tomogr 2016;10:364–74.

24. Nelson RC, Feuerlein S, Boll DT. New iterative reconstruction techniques for cardiovascular computed tomography: how do they work, and what are the advantages and disadvantages? J Cardiovasc Comput Tomogr 2011;5:286–92.

25. Blanke P, Schoepf UJ, Leipsic JA. CT in transcatheter aortic valve replacement. Radiology 2013;269:650–69.

26. Veronesi F, Corsi C, Sugeng L, et al. A study of functional anatomy of aortic-mitral valve coupling using 3D matrix transesophageal echocardiography. Circ Cardiovasc Imaging 2009;2:24–31.

27. Fukuda S, Saracino G, Matsumura Y, et al. Three-dimensional geometry of the tricuspid annulus in healthy subjects and in patients with functional tricuspid regurgitation. Circulation 2006;114:I492–8.

28. Chen JJ, Manning MA, Frazier AA, Jeudy J, White CS. CT angiography of the cardiac valves: normal, diseased, and postoperative appearances. Radiographics 2009;29:1393–412.

29. Budoff MJ. Maximizing dose reductions with cardiac CT. Int J Cardiovasc Imaging 2009;25:279–87.

30. Hoe LV, Marchal G, Baert AL, Gryspeerdt S, Mertens L. Determination of scan delay time in spiral CT-angiography: utility of a test bolus

injection. J Comput Assist Tomogr 1995;19:216–20.

31. Cademartiri F, Nieman K, Lugt Avd, et al. Intravenous contrast material administration at 16-detector row helical CT coronary angiography: test bolus versus bolus-tracking technique. Radiology 2004;233:817–23.

32. Bae KT. Intravenous contrast medium administration and scan timing at CT: considerations and approaches. Radiology 2010;256:32–61.

33. Kerl JM, Ravenel JG, Nguyen SA, et al. Right heart: split-bolus injection of diluted contrast medium for visualization at coronary CT angiography. Radiology 2008;247:356–64.

34. Yankelevitz DF, Gamsu G, Shah A, et al. Optimization of combined CT pulmonary angiography with lower extremity CT venography. AJR Am J Roentgenol 2000;174:67–9.

35. Bae KT, Seeck BA, Hildebolt CF, et al. Contrast enhancement in cardiovascular MDCT: effect of body weight, height, body surface area, body mass index, and obesity. AJR Am J Roentgenol 2008;190:777–84.

36. Pulerwitz TC, Khalique OK, Nazif TN, et al. Very low intravenous contrast volume protocol for computed tomography angiography providing comprehensive cardiac and vascular assessment prior to transcatheter aortic valve replacement in patients with chronic kidney disease. J Cardiovasc Comput Tomogr 2016;10:316–21.

37. Blanke P, Baumann T, Bulla S, et al. Prospective ECG-triggered CT angiography of the thoracic aorta in patients with atrial fibrillation or accelerated heart rates: feasibility and image quality. AJR Am J Roentgenol 2010;194:111–4.

KEY WORDS computed tomography angiography, transcatheter mitral valve repair/replacement, transcatheter tricuspid valve repair/replacement