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FOCUS ON TRICUSPID VALVE REPAIR

STATE-OF-THE-ART REVIEW

Tricuspid Valve S-Curves and Chamber Views

Implications for Transcatheter Tricuspid and Pulmonary Valve Interventions, Part 2 of the S-Curves and Chamber Views Series

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ABSTRACT

Despite the challenges associated with periprocedural imaging, transcatheter tricuspid valve interventions have shown important impact on outcomes. A comprehensive understanding of the anatomy of the right heart and surrounding structures is crucial. One way to optimize these interventions is by identifying the optimal fluoroscopic viewing angles along the S-curve of the tricuspid valve. Integration of chamber views using multimodality imaging (multislice computed tomography, fluoroscopy, and echocardiography) may increase operator confidence and reduce procedural duration, radiation exposure, contrast volume, and complication rates. (JACC Cardiovasc Interv. 2024;17:2713–2731) © 2024 by the American College of Cardiology Foundation.

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ABBREVIATIONS AND ACRONYMS

CAUD = caudal

CRAN = cranial

LAO = left anterior oblique

MSCT = multislice computed tomography

RAO = right anterior oblique

The rapid emergence of transcatheter tricuspid valve interventions has created new learning gaps in the field of structural intervention and periprocedural imaging. While transesophageal echocardiography (TEE) is the first-line imaging modality for patient selection and procedural guidance, spatial resolution of the tricuspid valve and surrounding structures is frequently challenging given the position of the heart relative to the path of the TEE probe, changes in cardiac orientation (ie, following prior open heart procedures), and/or the presence of pre-existing prostheses (eg, bioprosthetic valves and rings, pacemaker wires), combined with the limited echogenicity of delivery catheters and acoustic attenuation by prosthetic devices and delivery systems. These difficulties are readily apparent during catheter manipulations guided by “single-slice” 2-dimensional echocardiography and limited awareness of the surrounding 3-dimensional anatomy.[1] Until recently, however, little thought has been given to understanding the correlation between fluoroscopic and echocardiographic right heart imaging as a way to facilitate transcatheter tricuspid and pulmonary valve interventions.[2]

As in other structural heart interventions, multislice computed tomography (MSCT) can play an important role in understanding normal variations in right heart anatomy, as well as providing procedural guidance with respect to optimal chamber views derived from S-curves.[3] Optimal chamber views typically have 1 or more structures of interest in plane or en face and can therefore: 1) mitigate foreshortening and parallax of cardiac structures and delivery catheters; 2) allow accurate measurements (eg, distance and angles) between structures and/or devices; 3) guide intentional catheter manipulations; and 4) enable accurate device positioning. Matching echocardiographic and patient-specific MSCT-derived fluoroscopic chamber views allows the operator to get "the best of both worlds" with echocardiographic resolution of anatomy aligned with fluoroscopic positioning of delivery catheters and prostheses. In essence, matching echocardiographic and fluoroscopic chamber views provides a further step toward "fusing imaging in mind" as opposed to “on the screen.”[4]

Here, we aimed to: 1) describe S-curves and optimal chamber views for right-sided heart valve interventions; 2) ascribe attitudinal descriptors (ie, anterior/posterior, right/left, superior/inferior) to specific chamber views; 3) describe the anatomic relationship of the tricuspid valve and its components to surrounding cardiac structures; and 4) integrate and translate this knowledge for transcatheter tricuspid and pulmonary valve interventions. This review aims to enhance understanding of imaging and catheter maneuvers by describing the attitudinal position of cardiac structures without replacing existing tricuspid valve nomenclature.

RIGHT-SIDED CHAMBER VIEWS AND S-CURVES

CHAMBER VIEWS. The basic principle is that the classical echocardiographic chamber views (1-chamber/short axis or bicaval, 2-chamber or right ventricular inflow, 3-chamber or right ventricular inflow/outflow, and 4-chamber) can all be obtained with a range of cardiovascular imaging modalities (ie, fluoroscopy, MSCT, magnetic resonance imaging, and nuclear imaging). Harmonizing chamber views (eg, fluoroscopy to echocardiography) can foster a “common language” that enables the operator to translate anatomical knowledge from one imaging modality to another.

Simulated fluoroscopic chamber views of the right heart can be generated using MSCT volumetric data. The 1-chamber view of the right ventricle can be viewed in the left anterior oblique (LAO) caudal (CAUD) quadrant, the 2-chamber in right anterior oblique (RAO) CAUD, the 3-chamber in shallow RAO cranial (CRAN), and 4-chamber in extreme CRAN (**Figure 1**).[5] “Blended” chamber views (eg, hybrid

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The authors attest they are in compliance with human studies committees and animal welfare regulations of the authors’ institutions and Food and Drug Administration guidelines, including patient consent where appropriate. For more information, visit the Author Center.

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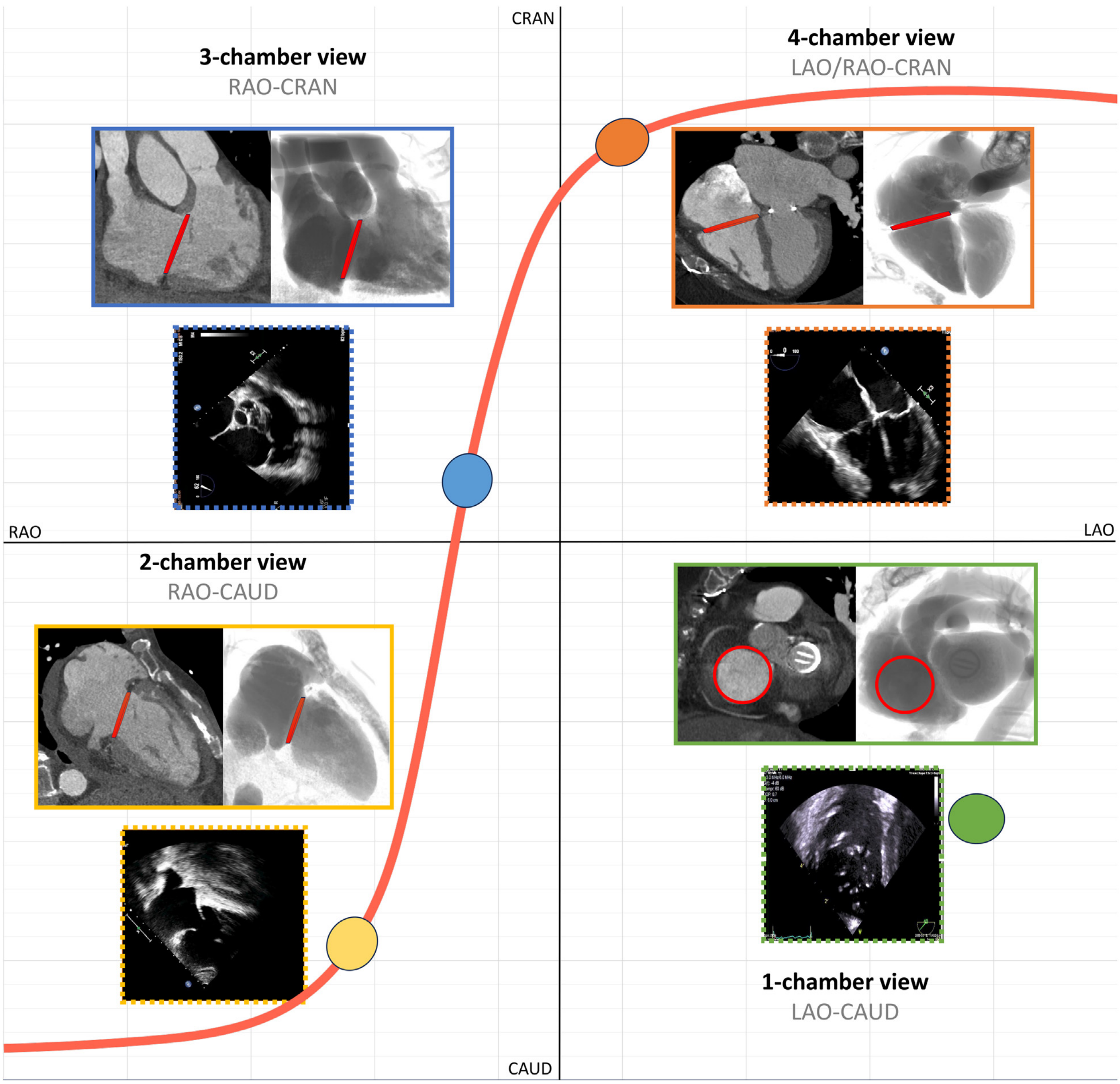
FIGURE 1 Tricuspid Valve Annulus S-Curve and Chamber Views



Chamber views are consistently color-coded throughout the review: 1-chamber (green), 2-chamber (yellow), 3-chamber (blue), 4-chamber (orange), tricuspid annulus S-curve (red). CAUD = caudal; CRAN = cranial; LAO = left anterior oblique; RAO = right anterior oblique.

2- and 3-chamber views) can also be obtained while transitioning across the fluoroscopic grid.

The concept of fusion imaging between echocardiography and fluoroscopy shows that chamber views are universal across imaging modalities, aiding in pinpointing wires and catheters relative to right heart chambers and the tricuspid valve annulus (Figure 2).

S-CURVES. The S-curve represents a mathematical expression of the perpendicular vector within the plane of interest. As the S-curve traverses the fluoroscopic quadrants, it produces chamber views where the structure of interest is consistently in plane (Figure 1).[6] Optimal chamber views typically have 1 or more structures of interest in plane or en face and can

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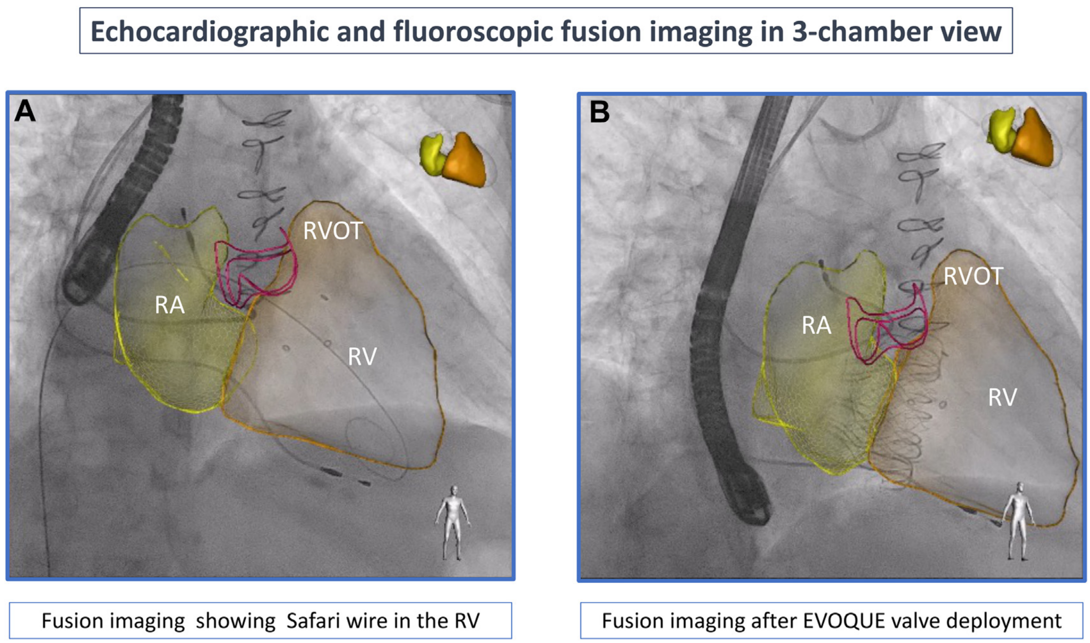
FIGURE 2 The Role of Intraprocedural Fusion Imaging for Transcatheter Tricuspid Valve Replacement



This figure describes the role of transesophageal echocardiography and fluoroscopic chamber view fusion imaging during transcatheter tricuspid valve replacement with EVOQUE valve. (A) The initial placement of the Safari wire in the right ventricle (RV). (B) The final deployment of the EVOQUE valve in the right heart 3-chamber view (shallow RAO CRAN). RA = right atrium; RVOT = right ventricle outflow tract; other abbreviations as in Figure 1.

be obtained by observing the intersection and/or relationship between 2 or more S-curves (Figure 3).

Appreciating the fluoroscopic quadrant where the S-curve of a structure does not intersect can also be informative, as it represents the chamber view with that structure seen en face (ie, in short axis). Figure 3 summarizes the patterns in which several structures are in plane or en face across the various chamber views. As will be further elucidated throughout this review, the 1-, 3-, and 4-chamber views play a crucial role in guiding and understanding transcatheter tricuspid valve interventions.

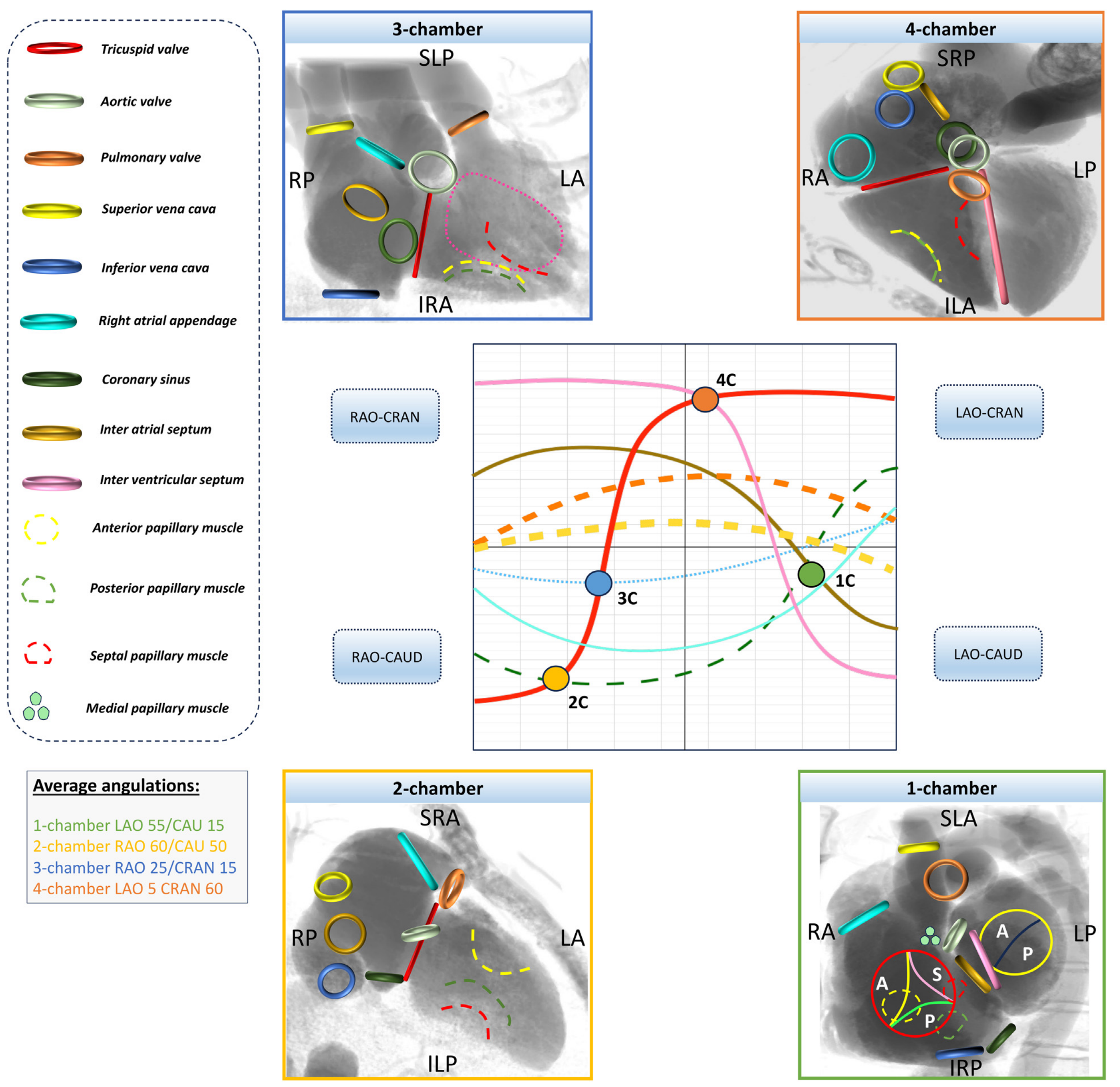
ATTITUDINAL DESCRIPTION OF RIGHT-SIDED FLUOROSCOPIC CHAMBER VIEWS

The traditional "Valentine" method, which describes cardiac anatomy with the heart standing on its apex using terms like “lateral” vs “septal,” overlooks the heart’s actual anatomical orientation. This is problematic with increasing use of MSCT and fluoroscopy for guiding catheter manipulation. The attitudinal orientation of cardiac structures is based on anatomical position: the subject is upright facing the observer, with the right side on the observer’s left. Proximity to the observer is anterior, farther structures are posterior, superior is toward the head, and inferior is toward the feet. Describing the right atrium and ventricle as "right-sided" compared with the left counterpart is misleading; they are actually anterior and only slightly rightward (Figure 4).[7] The addition of attitudinal descriptors to chamber views can reinforce the common language needed for multimodality imaging. Figure 3 displays the attitudinal orientation across chamber views.

RIGHT-SIDED CHAMBER VIEWS AND ANATOMY

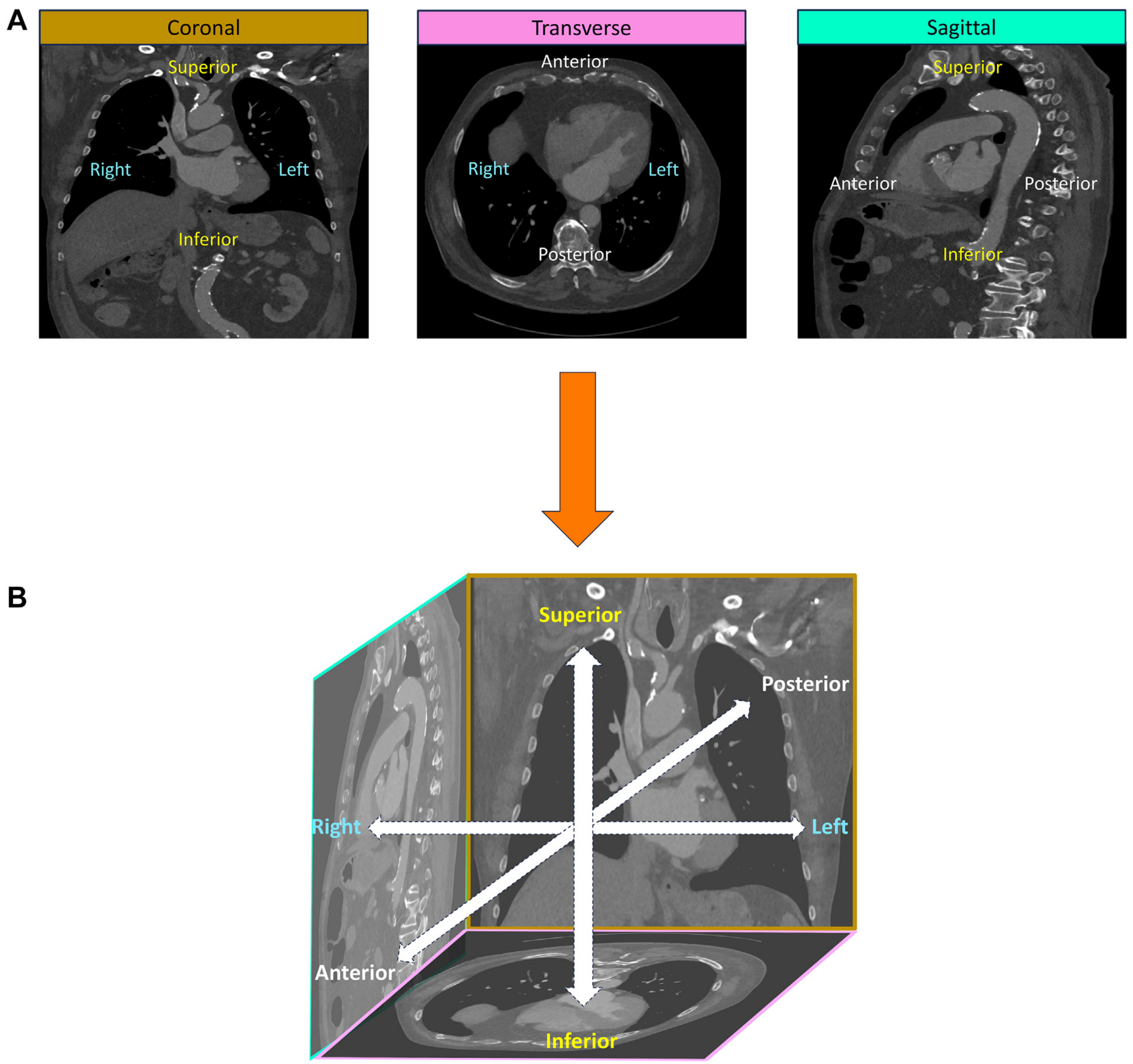
ONE-CHAMBER AND BICAVAL VIEWS OF THE RIGHT HEART. The 1-chamber view of the right heart is obtained in the LAO CAUD projection (average fluoroscopic angulation: LAO 55°/CAU 15°).[8] The corresponding echocardiographic images include the

FIGURE 3 **Anatomy and Relationship Between the Tricuspid Annulus S-Curve and Selected Right Heart Structures**



The anatomical pattern appreciated on the simulated fluoroscopic images (computed tomography derived) can be translated to any imaging modality. For example, the pulmonary valve, tricuspid valve, and vena cava can all be found near in plane on the 3-chamber (3C) echocardiographic view (though they may not be appreciated as such). Anatomical structures are represented by colored continuous or dotted circles, with corresponding text box explanations. Structures are displayed in in-plane, en face, or oblique orientations. The optimal projection curve of the tricuspid annulus is plotted as a continuous red line, the inferior vena cava as a dotted blue line, the superior vena cava as a dotted yellow line, the coronary sinus as a dotted green line, the pulmonary valve as a dotted orange line, the right atrial appendage as a continuous teal line, the interventricular septum as a dotted pink line, and the interatrial septum as a continuous brown line. The regions of fluoroscopic angulations showing the tricuspid valve annulus and some of the surrounding structure in plane are indicated by circles with the corresponding chamber views. The attitudinal orientation of each chamber view is added on each panel. *The average views have been previously published.[16] The average views may not necessarily reflect the intersection of S-curves in this example, given the possible standard deviations. For example, a 3C view with the inferior vena cava and tricuspid valve annulus in plane can be identified in RAO 30° shallow CAUD, RAO 30° shallow CRAN, or simply RAO 30° across 3 different patients, respectively. 1C = 1-chamber; 2C = 2-chamber; 4C = 4-chamber; A = anterior; I = inferior; ILA = inferior-left-anterior; ILP =inferior-left-posterior; IRA = inferior-right-anterior; IRP = inferior-right-posterior; L = left; LA = left atrium; LP = left-posterior; P = posterior; R = right; RA = right atrium; RP = right-posterior; S = superior; SLA = superior-left-anterior; SLP = superior-left-posterior; SRA = superior-right-anterior; SRP = superior-right-posterior; other abbreviations as in Figure 1.

FIGURE 4 Pure Attitudinal Orientations Provided by the Coronal, Transverse, and Sagittal Views



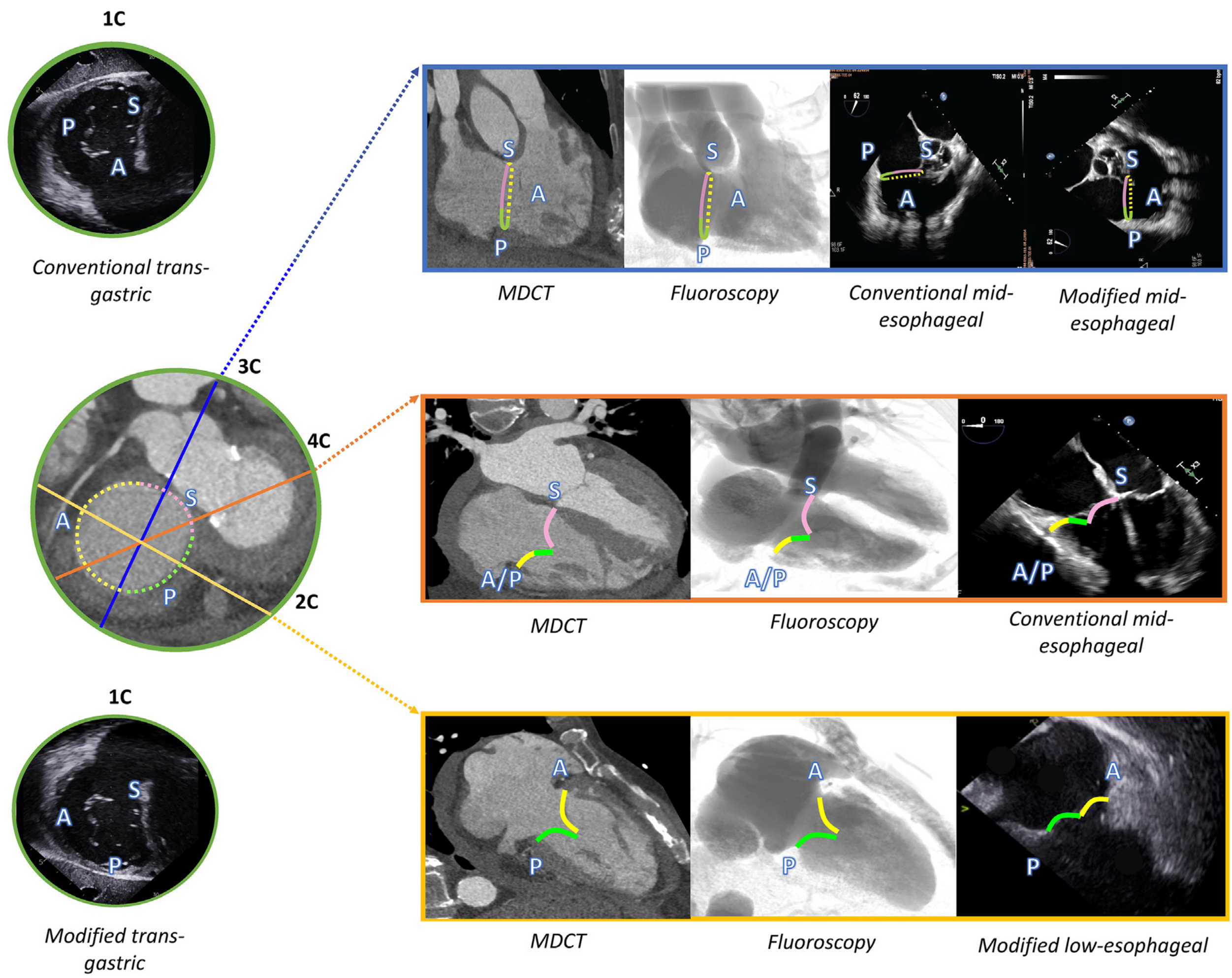
(A) The coronal view (brown panel) offers a true appreciation of superior vs inferior and right vs left; the transverse view (pink panel), anterior vs posterior and right vs left; and the sagittal view (teal panel), superior vs inferior and anterior vs posterior. (B) Three-dimensional representation of these attitudinal orientations.

transthoracic parasternal short-axis and transesophageal transgastric basal short-axis views (0°-20°). It is important to realize, and a potential source of confusion, that the aortic valve is typically located at 1 o'clock relative to the en face view of the tricuspid valve annulus, whereas it is positioned at roughly 5 o'clock on the transesophageal transgastric view. Nonetheless, the attitudinal orientation of cardiac structures remains the same.

The S-curve of the tricuspid valve annulus does not travel across the LAO CAUD quadrant and therefore the 1-chamber view displays the tricuspid valve annulus en face (ie, in short axis).

Assuming a trileaflet configuration, the computed tomographic (or fluoroscopic) 1-chamber view reveals that: 1) the posterior leaflet of the tricuspid valve lies inferoposterior to the anterior leaflet and inferoanterior to the septal leaflet; 2) the anterior leaflet

FIGURE 5 Tricuspid Valve Leaflets According to Chamber Views



Starting from the en face view of the TA, the corresponding sections that generate the 2-, 3-, and 4-chamber views can be appreciated. With reference to the attitudinal orientation of the 1-chamber view, the 3-chamber view is generated by a relatively "superior-to-inferior" cut that clearly separates the anteroseptal, posteroseptal, and anteroposterior commissures, while the anterior leaflet runs across most of the length of the tricuspid valve annulus. The 4-chamber view is generated by a relatively "anteroposterior" cut and demonstrates the combination of either anteroseptal or posteroseptal leaflets (depending on how superior or inferior the 4-chamber cut is made). The 2-chamber view is generated by cutting across the right atrial appendage and coronary sinus from "anterosuperior" to "posteroinferior" and demonstrates the adjacent anterior and posterior leaflets, respectively. MDCT = multidetector computed tomography; other abbreviations as in Figure 3.

lies anterior to the septal leaflet and anterosuperior to the posterior leaflet; and 3) the septal leaflet lies posterior to the anterior leaflet and posterosuperior to the posterior leaflet.[9,10] In a broad sense, the posterior leaflet is "inferior," the anterior leaflet "anterior," and the septal leaflet "posterior" within the attitudinal framework (Figures 3 and 5). The tricuspid valve annulus typically dilates from its superior posterior aspect (ie, fibrous anchoring of the septal leaflet) toward the inferior anterior right ventricular free wall. As this axis dilates: 1) gaps are typically located in the anteroseptal and posteroseptal commissures; and 2) the major axis of the tricuspid valve annulus is usually appreciated in the 3-chamber view.

The tricuspid valve apparatus may include 4 distinct papillary muscles (anterior, posterior, septal, and the less well known medial papillary muscle complex). The tip of the anterior papillary muscle is the most prominent and consistently located within the anterosuperior portion of the tricuspid valve annulus in the short-axis 1-chamber view. The anterior papillary muscle arises from 2 distinct branches located in the superior half of the right ventricular apex: 1) anteriorly from the right ventricular free wall; and 2) posteriorly from a branch of the moderator band that arises from the ventricular septum.[11] The anterior papillary muscle has chordal attachments to the anterior and posterior leaflets and is usually used as a landmark to separate the anterior and posterior tricuspid valve leaflets. The posterior papillary muscle is the most inferior and typically smaller (sometimes multiple) with chordal attachments to the posterior and septal leaflets.[12] The septal papillary muscle is the smallest, lying posterior to its anterior counterpart and may manifest as various small muscle bands that originate from the septum, featuring chordal attachments to the anterior and septal leaflets. Notably, this structure is absent in approximately 20% of hearts. The medial papillary muscle complex, also known as the "papillary muscle of Lancisi," exhibits high variability, potentially consisting of 1, 2, or multiple smaller muscles. It is the most superior papillary muscle, originating close to the right ventricular outflow tract and may be characterized by chordal attachments to both the anterior and septal tricuspid leaflets (**Figure 3**).[13,14]

Starting from 11 o'clock (superoanterior) and moving clockwise toward 6 o'clock (posteroinferior) on the 1-chamber view, the tricuspid valve annulus is surrounded by the right atrial appendage, superior vena cava, pulmonary valve, noncoronary cusp of the aortic valve, superimposed atrial and membranous septum adjacent to the noncoronary cusp of the aortic valve, atrial septum, coronary sinus, and inferior vena cava (**Figure 3**).

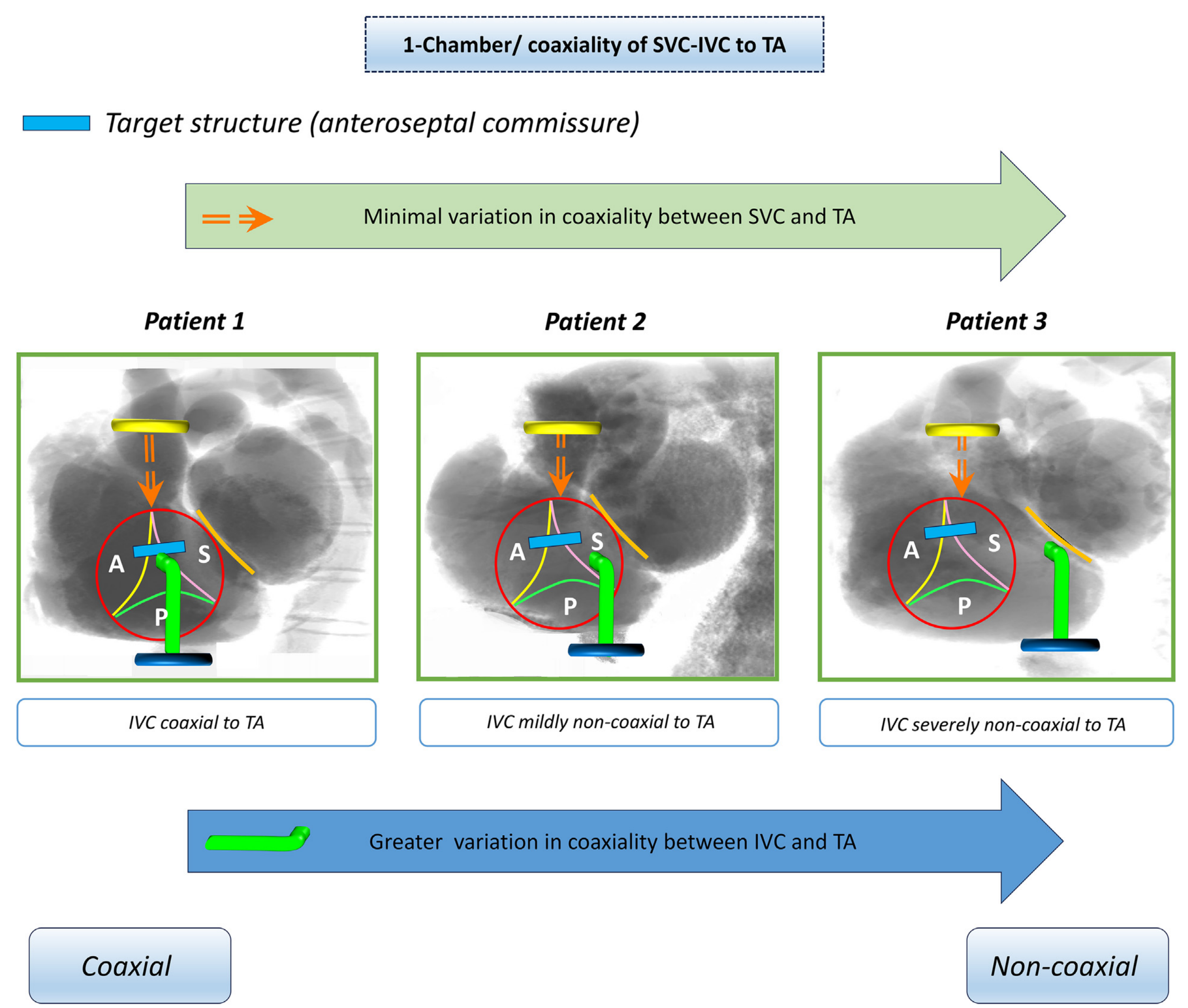
The 1-chamber view of the right heart in LAO CAUD provides valuable information about the true geometric relationship of cardiac structures for 2 main reasons: 1) many right heart structures have their S-curves intersecting in this quadrant; and 2) the tricuspid and mitral valve annuli appear en face. More specifically, the S-curves of the following structures course through the LAO CAUD quadrant: the right atrial appendage, inferior vena cava, superior vena cava, interatrial septum, interventricular septum, and coronary sinus (**Figure 3**). Having these structures in plane or en face is critical to mitigating parallax and foreshortening while understanding the distance or angular relationship between 2 or more of these structures on 2-dimensional imaging. Thus, the 1-chamber view can provide important insights into anatomical variability. **Figure 6** demonstrates that while the inferior vena cava and atrial septum maintain an inferosuperior relationship to one another, this complex may shift posteriorly and become off-centered from the tricuspid valve annulus; meanwhile, the superior vena cava remains relatively coaxial with the tricuspid valve annulus, with less variation in this respect. In **Figure 6** (patient 1), a catheter emerging from the inferior vena cava would enter the right atrium coaxial to the tricuspid valve annulus after leftward flexion. On the other hand, in **Figure 6** (patient 3) the inferior vena cava is not coaxial with the tricuspid valve annulus, and a catheter will require initial anterior flexion before "diving down" (ie, attitudinally leftward) toward the center of the tricuspid valve annulus. This latter scenario may create the "septal hugger" phenomenon, whereby the delivery catheter abuts against the septum and encounters difficulty in achieving coaxiality with the tricuspid valve annulus prior to anterior flexion; a relatively low-lying atrial septum can also exacerbate this phenomenon. Given the anatomic proximity between the anteroseptal commissure and atrial septum, transcatheter-edge-to-edge interventions can be challenging in the presence of a "septal hugger," owing to difficulties with coaxial access to the anteroseptal commissure. For these reasons, transcatheter tricuspid valve delivery systems entering from the inferior vena cava are designed with additional anterior (or "lateral") flex capabilities to circumvent the noncoaxial inferior vena cava and potential "septal hugger." In contrast, the ostium of the superior vena cava is usually located anterior to that of the inferior vena cava, providing better coaxiality to the tricuspid valve annulus without the need for additional flexion during transjugular procedures (**Figure 6**).[15]

TWO-CHAMBER (RIGHT VENTRICULAR INFLOW) VIEW OF THE RIGHT HEART. The 2-chamber view of the right heart can be obtained in a steep RAO CAUD projection (average fluoroscopic angulation: RAO 60°/CAUD 50°).[4,8] TEE can display a similar 2-chamber view in a midesophageal 100° to 120° (bicaval angle, rotated toward the right), a low-esophageal right atrial view or a transgastric right ventricular inflow (long-axis) view at 110° to 130°.

The 2-chamber view provides the anterior leaflet superiorly and, depending on anatomic or cross-section variability, the septal or posterior leaflet inferiorly (or in some instances, the posteroseptal commissure) (**Figure 5**).[4]

The 2-chamber view of the right heart displays the atrial septum en face, while the superior and inferior vena cava run above and below, respectively, the former albeit lying slightly more anterior than the latter (**Figure 3**). This view is optimal for assessing whether a transseptal puncture is overlapping with the aortic root.

FIGURE 6 Anatomical Variability (Coaxiality) Between the IVC/SVC and TA Using the 1-Chamber View



The inferior vena cava (IVC) and atrial septum are appreciated in plane while the tricuspid valve is seen en face. The left and right of the screen represent the anterior and posterior attitudinal locations. The figure demonstrates 3 different patients with varying relationships between the IVC and tricuspid valve annulus (TA). Moving from patient 1 to 3, the IVC becomes noncoaxial with the TA by virtue of its progressive posterior displacement. In patient 3, a catheter would require anterior flexion before "diving" leftward toward the TA. The superior vena cava (SVC) and IVC are represented by yellow and blue rings, respectively. The green catheter and orange dotted arrows indicate the TA approaches from the IVC and SVC, respectively. While there is minimal variation in coaxiality among patients in the SVC approach, greater variation is evident in the IVC approach. Abbreviations as in Figure 3.

The S-curves of the coronary sinus and tricuspid valve annulus intersect in the 2-chamber view of the right ventricle and can be found at 90° to 120° from each other (Figure 3). A fluoroscopic steep RAO CAUD projection permits maximal separation between these 2 structures and can guide the operator to navigate across the tricuspid annulus efficiently from the right atrium while avoiding inadvertent cannulation of the coronary sinus (Figure 7).

THREE-CHAMBER (RIGHT VENTRICULAR INFLOW/OUTFLOW) VIEW OF THE RIGHT HEART. The 3-chamber view of the right heart is obtained in an RAO projection with slight CRAN angulation (average fluoroscopic angulation: RAO 25°/CRAN 15°).[8] A corresponding TEE image can be obtained from a 60° to 90° midesophageal, lower esophageal, or transgastric view.[4] It is important to note that the orientation of the tricuspid annulus differs between the

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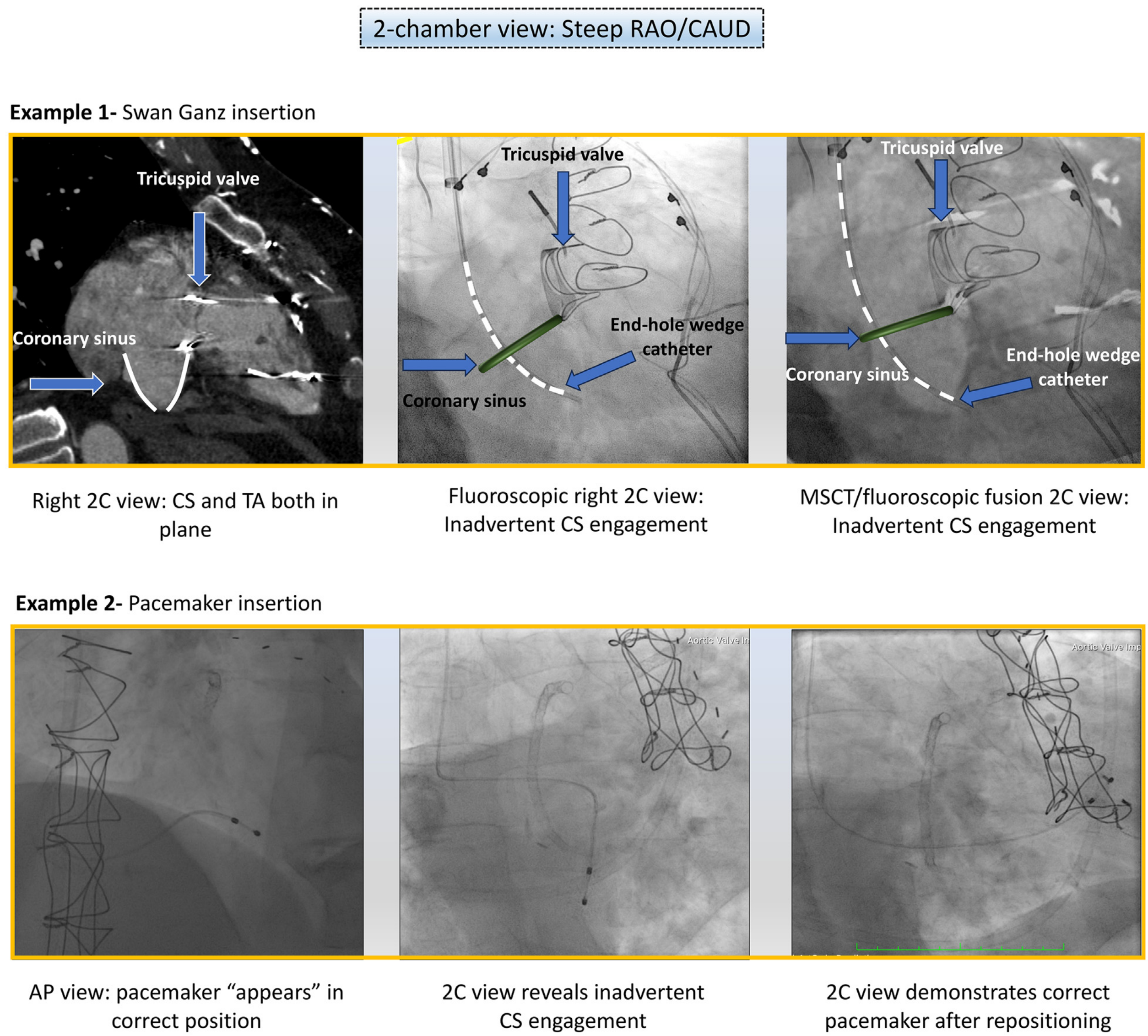
FIGURE 7 Role of the 2C View in Right Heart Procedures



In the 2C view (steep RAO/CAUD), both the TA and coronary sinus (CS) are in plane, not overlapped, and clearly demarcated from each other. This view is helpful during those procedures (eg, hemodynamic right heart catheterization, pacemaker insertion, endomyocardial biopsy) in which catheter passage from the right atrium to right ventricle becomes challenging as a result of catheter engagement in the CS, rather than in the TA. The figure demonstrates 2 such examples—note that the catheters are pointed "downward" and posterior toward the CS, as opposed to going horizontal and "leftward" across the TA. It is axiomatic that the 1C view can provide similar guidance when the TA is en face while the CS is in plane. AP = anteroposterior; MSCT = multislice computed tomography; other abbreviations as in Figures 1, 3, and 6.

fluoroscopic and echocardiographic viewing screen; in the former, it runs from 12 to 6 o'clock, and in the latter, from 3 to 9 o'clock. Nonetheless, the attitudinal descriptors remain the same.

The S-curve of the tricuspid valve annulus intersects across the 3-chamber view of the right heart. The right ventricular outflow tract is clearly appreciated in the superior half of the right ventricle, while the anterior, posterior, and septal papillary muscles are "out of the way" in the inferior half (Figure 3). The attachments of the septal and posterior leaflets are positioned relatively superior and inferior on the tricuspid valve annulus, respectively, while much of the anterior leaflet runs from superior to inferior across the annulus. The corollary implies that the anteroseptal and posteroseptal commissures are on the superior and inferior aspect of the annulus, respectively, in the 3-chamber view (**Figure 5**).

The 3-chamber view elongates the inflow/outflow portions of the right heart because the inferior and superior vena cava, tricuspid valve, and pulmonary valve annuli are concomitantly in-plane; their S-curves all nearly intersect in a shallow RAO CRAN projection (**Figure 3**). Given that these structures are in plane, the delivery angle and distance between the inferior/superior vena cava and tricuspid valve annulus can be measured accurately. This view mitigates foreshortening of delivery catheters by “stretching open” the anatomy, thereby facilitating procedures that require advancement of catheters from right atrium to pulmonary artery (such as Swan-Ganz catheters for right heart catheterization, ProtekDuo right heart assist devices [LivaNova], and transcatheter tricuspid and pulmonary valve replacement). As shown in **Figure 8**, the 3-chamber view minimizes foreshortening of the anatomy and a SAPIEN delivery catheter while maintaining the tricuspid valve annulus in plane.

Similar to the 1-chamber view, the 3-chamber view can also provide important insights into anatomical variability (**Figure 9**). Although the angle between the inferior vena cava and tricuspid valve annulus remains fairly constant at or around 90° (87 ± 12°) in virtually all patients, the distance from inferior vena cava to tricuspid valve annulus can vary, with implications for the manipulation of catheters with respect to the height required across the tricuspid valve annulus (**Figure 9**).[16] As will be further elucidated subsequently (see Catheter Manipulations Across Chamber Views), the 3-chamber view defines catheter flexion and travel from right to left across the vertically oriented tricuspid valve annulus after anterior flexion determined in the 1-chamber view. The 3-chamber view is essential for wire placement in the right ventricular apex, as it isolates the right ventricular outflow tract and naturally provides a "chordal/papillary" free zone. This view is also helpful in procedures requiring septal anchoring where the interventricular septum is en face.

FOUR-CHAMBER VIEW OF THE RIGHT HEART. The 4-chamber view of the right heart is obtained in a steep CRAN projection with very shallow RAO or LAO angulation (average fluoroscopic angulation: LAO 5°/CRAN 60°), corresponding to the mid-to-low TEE view at 0° to 20°.[4]

The S-curve of the tricuspid valve annulus intersects with the steep CRAN projection in shallow RAO/LAO, thereby providing the 4-chamber view with the tricuspid valve annulus in plane (**Figures 3**). Given that the anterior and posterior papillary muscles are positioned relatively superior and inferior to each other, the superoanterior 4-chamber view separates the anterior and septal papillary muscles (and, conversely, the inferoposterior 4-chamber view separates the posterior and septal papillary muscles). As would be expected, the superoanterior and inferoposterior 4-chamber views enable visualization of the anteroseptal and posteroseptal leaflet combinations, respectively (**Figure 5**).

As opposed to 2-dimensional echocardiography, the fluoroscopic 4-chamber view overlaps the superoanterior and inferoposterior 4-chamber views, resulting in overlap of the anterior and posterior papillary muscles (while separating the septal papillary muscles along the posteriorly positioned ventricular septum).

The 4-chamber view holds important information about the true geometric relationship between the inferior vena cava and tricuspid valve annulus. Given that the inferior vena cava is en face and the tricuspid valve annulus in plane, the offset and distance from the inferior vena cava to the tricuspid valve annulus can be appreciated (as shown in the 1- and 3-chamber views, respectively) (**Figure 10**). As will be discussed subsequently, an understanding of the 1-, 3-, and 4-chamber views is of critical importance in achieving coaxial positioning and centralization across the tricuspid valve annulus during transcatheter tricuspid valve repair or replacement procedures. Furthermore, the fluoroscopic 4-chamber view can be used to guide procedures that aim for the ventricular septum (eg, pacemaker implantation, endomyocardial biopsy, and ventricular septal defect closure).[17]

CATHETER MANIPULATIONS GUIDED BY CHAMBER VIEWS

Purposeful navigation of catheters around the heart requires an understanding of the attitudinal orientation of echocardiographic and fluoroscopic images. An approach from the femoral vein implies that the push-and-pull maneuver will move catheters along the superior and inferior axis, respectively, while clockwise and counterclockwise rotations (after flexing toward the tricuspid valve) will move in the posterior and anterior axis, respectively (**Figure 11**). An approach from the jugular vein has the opposite implications given the “mirror image” analogy. Owing to the orientation of the x-ray tube/image intensifier, it is more intuitive to identify attitudinal locations on the fluoroscopic screen rather than the echocardiographic image. For

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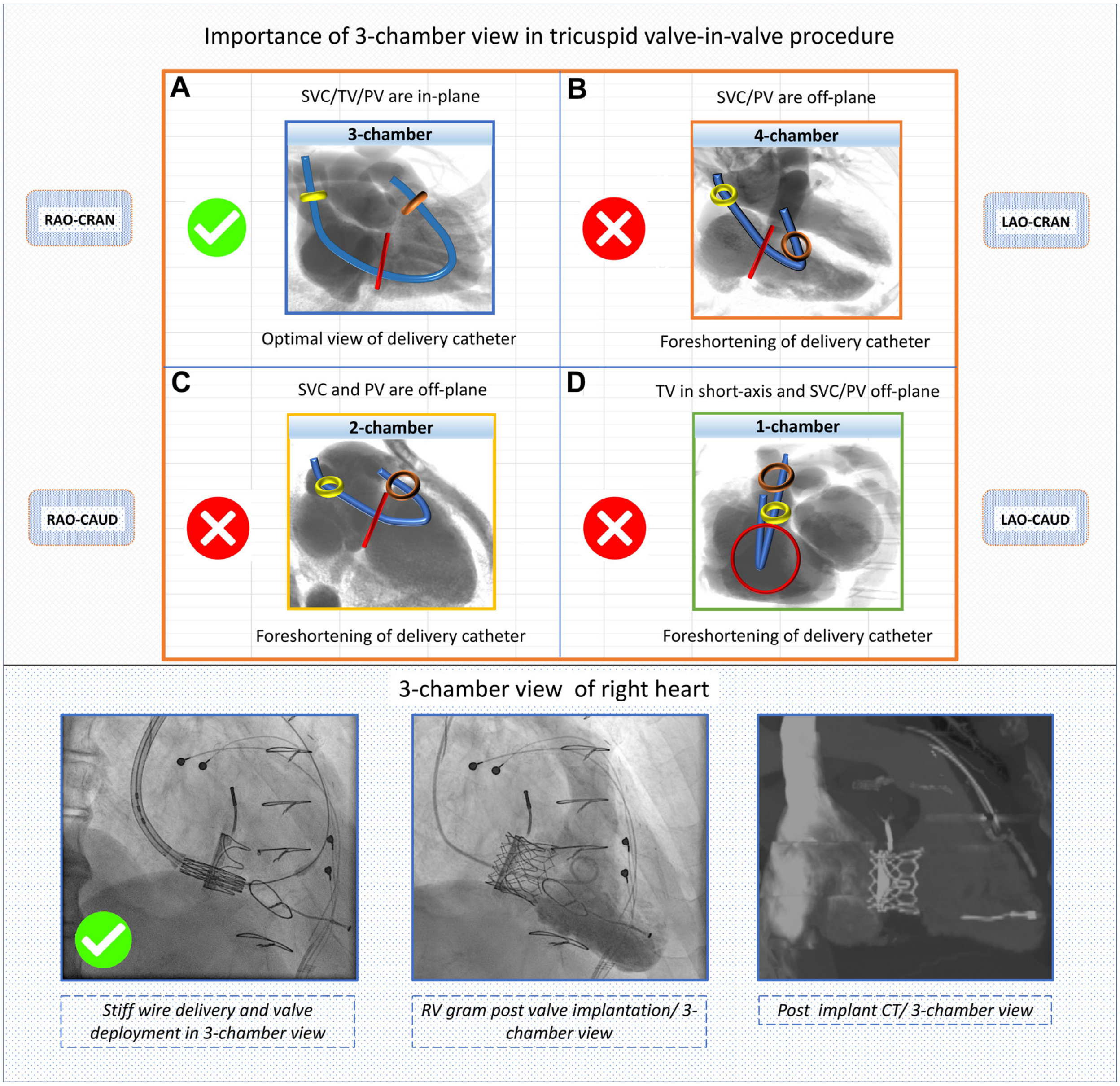
FIGURE 8 **Application of the 3-Chamber View During Transcatheter TV Interventions**

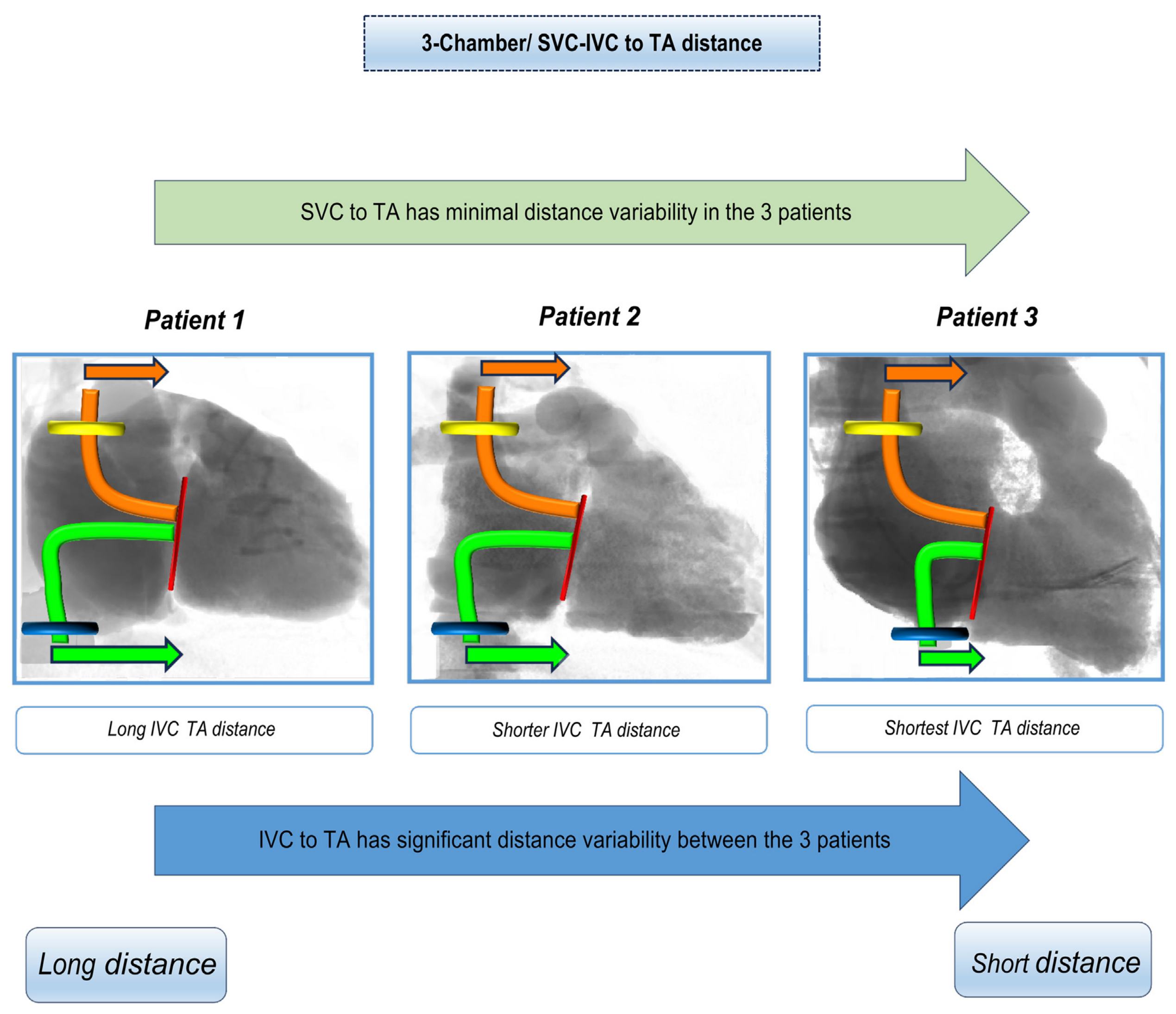


(A) The 3-chamber view, also known as the right ventricular outflow tract (or inflow/outflow) view, displays the SVC/IVC, TA, and pulmonary valve (PV) in plane, mitigates foreshortening of delivery catheters as a direct consequence of "opening up" the inflow and outflow tracts, and provides optimal feedback on push-pull catheter maneuvers. Panels B, C, and D clearly demonstrate parallax associated with the delivery catheter (in blue), as the necessary structures are not all in-plane. TV = tricuspid valve; other abbreviations as in Figures 1 and 6.

example, pushing catheters superiorly from a transfemoral approach (eg, from posteroseptal to anteroseptal commissure) can be counterintuitive on transesophageal short-axis imaging, given that catheters appear to be moving from superior to inferior on the fluoroscopic screen.

NAVIGATING ACROSS THE 1-CHAMBER VIEW. By superimposing a 12-hour clock onto the en face view of the tricuspid valve, it becomes clearer that counterclockwise rotation of catheters from a transfemoral venous approach will direct them anteriorly toward the anterior leaflet, while clockwise rotation will

FIGURE 9 3-Chamber View for Anatomic Variability Between IVC and TA



This figure demonstrates the varying distance between the IVC and TA (ie, height) in 3 separate patients (who also feature in Figure 8). The fact that the IVC and TA are both in-plane in the 3-chamber view allows an appreciation of the distance and angle between the 2 structures. For instance, patient 3 has the shortest distance between the IVC and TA and may require specific catheter manipulations to gain more height if required. There is less variation in the angle between the IVC and TA. Yellow and blue rings represent the SVC and IVC, respectively, while green and orange catheters represent the transfemoral and transjugular approaches, respectively, toward the TA. Variable-sized orange arrows denote the distance between the SVC and TA, while green arrows represent the distance between the IVC and TA. Abbreviations as in Figure 6.

direct them posteriorly toward the septal leaflet (Figure 11). These respective movements can also be achieved with dedicated delivery system features, such as the lateral and septal knobs found on the TriClip system (Abbott) (Supplemental Figure 1). However, despite being labeled the "lateral" knob, its function is to displace catheters anteriorly away from the septum in patients whose inferior vena cava is posteriorly displaced (and not coaxial with the tricuspid valve annulus), thereby avoiding "septal hugging." Pushing a coaxial catheter superiorly from the inferior vena cava will generally direct it from the posteroseptal to anteroseptal commissure.

An approach from the superior vena cava requires opposite movements to achieve similar results. For example, counterclockwise catheter rotation will direct it posteriorly toward the septal leaflet.

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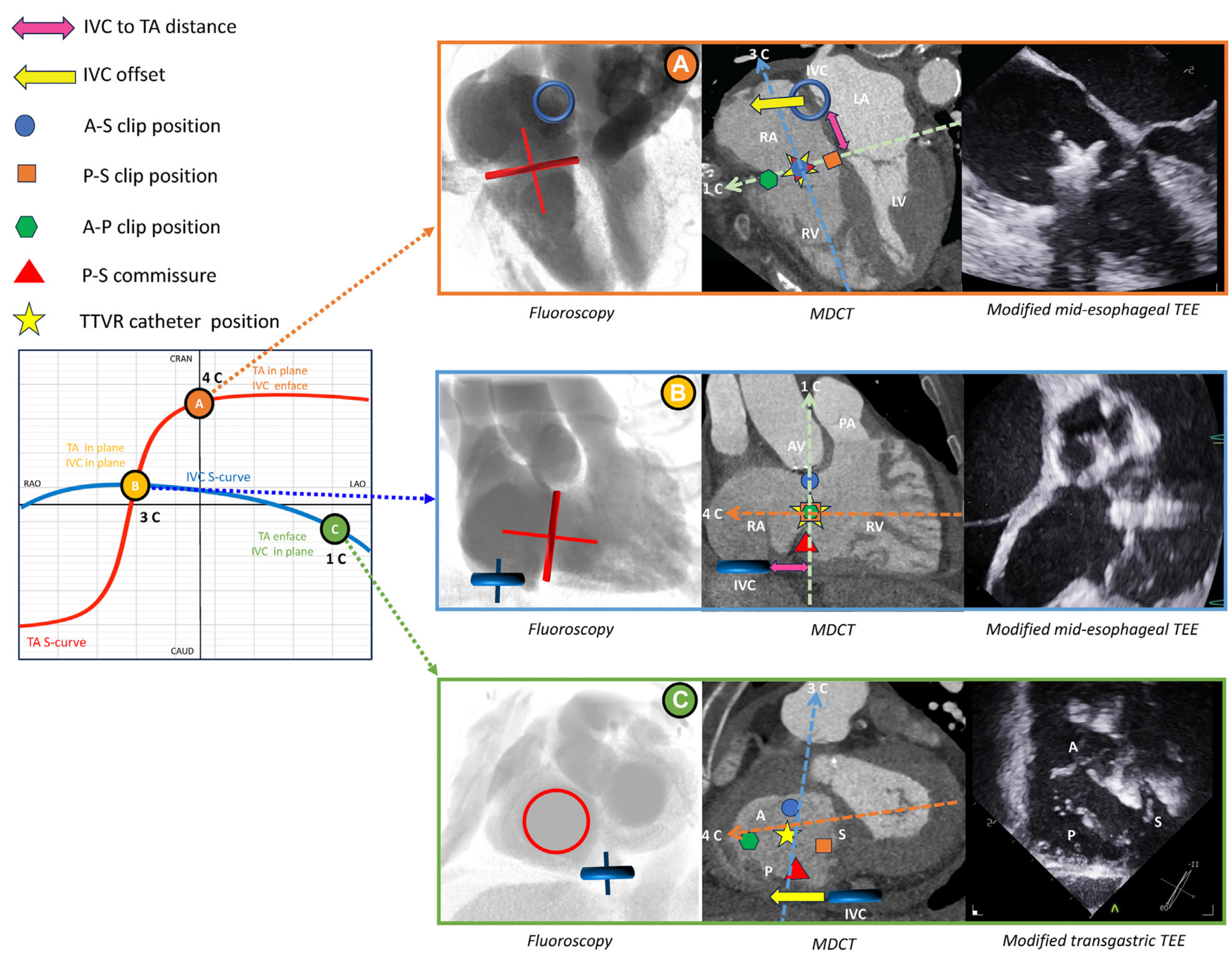
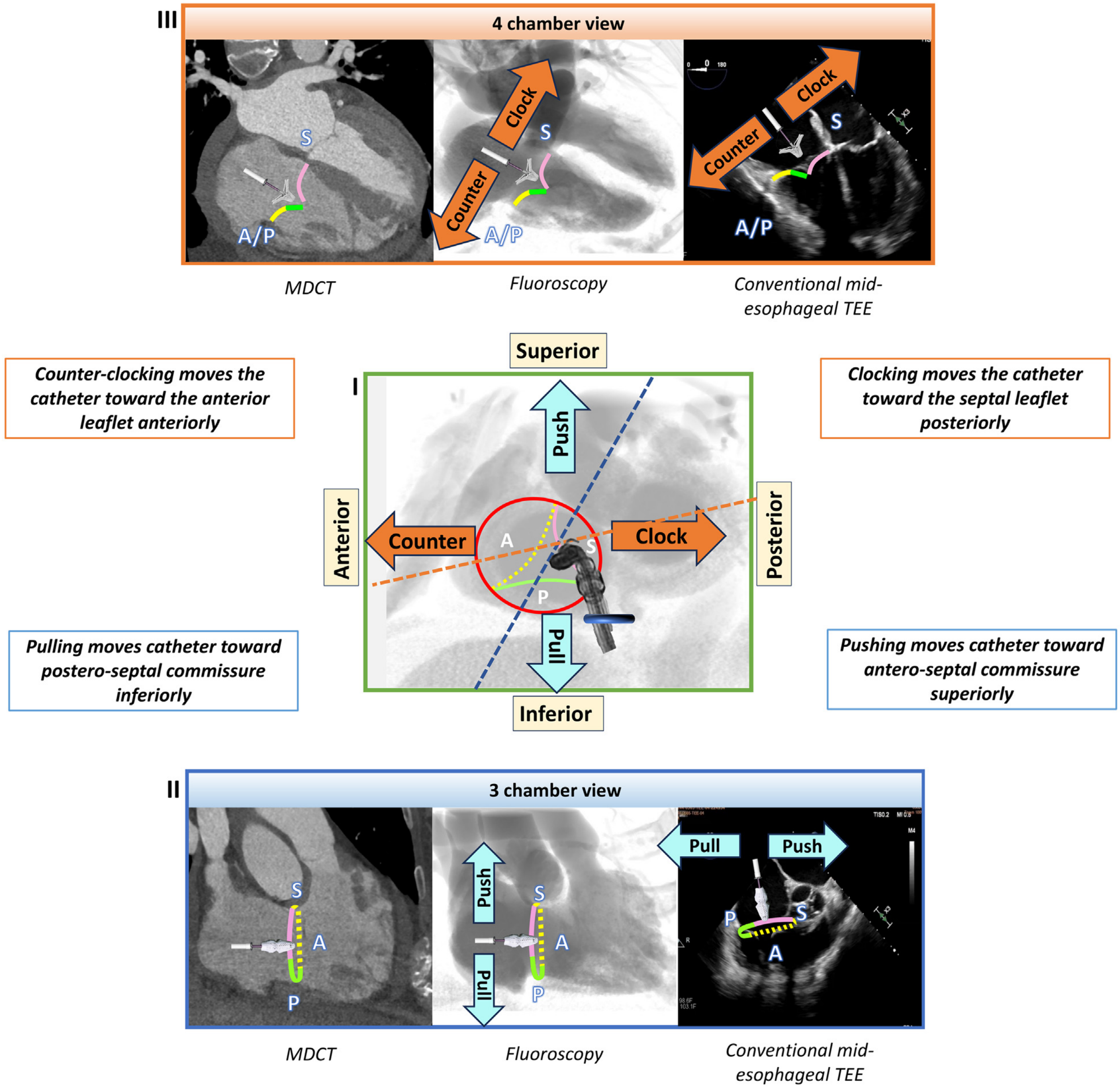
FIGURE 10 Combining the 1C, 3C, and 4C Views to Obtain Delivery Catheter Centralization and Coaxiality Across the TA



The figure displays the S-curves of the TA (red line) and IVC (blue line). The 1-, 3-, and 4-chamber views provide various combinations of the TA and IVC in plane and/or en face. Circle A on the S-curves represents the 4C view in which the TA is in plane and the IVC is en face. Circle B represents the 3C view where both the TA and IVC are in-plane. Circle C represents the 1C view in which the IVC is in plane and the TA is en face. Corresponding and matching multislice computed tomography, fluoroscopic, and modified transesophageal views of the 1C (green panel), 3C (blue panel), and 4C (orange panel) views. The 1C view is necessary for centralization, whereas the 3C and 4C views are necessary for coaxiality and depth positioning across the TA—all can be obtained during X-plane or multiplanar echocardiographic reconstruction. The direction of catheter movements can be better understood by appreciating how the cut-planes for the 3C and 4C views are generated from the short-axis (1C) view—the push/pull and clockwise/counterclockwise maneuvers are appreciated on the 3C and 4C views, respectively. Colored shapes illustrate catheter positions across chamber views, with corresponding ideal positions for transcatheter tricuspid valve replacement (TTVR), and clip catheters are provided in the explanatory text box. A-P = anteroposterior; A-S = anteroseptal; AV = aortic valve; P-S = posteroseptal; MDCT = multidetector computed tomography; PA = pulmonary artery; RA = right atrium; RV = right ventricle; TEE = transesophageal echocardiography; other abbreviations as in Figures 3 and 6.

NAVIGATING ACROSS THE 3-CHAMBER VIEW. Pulling movements will direct catheters inferiorly toward the posteroseptal commissure, while pushing will direct catheters superiorly toward the anteroseptal commissure (Figure 11). Dedicated delivery system features, such as the Flex (F) or Plus (+) knob found on the TriClip system, allow the catheter to flex or deflect toward (and ultimately become perpendicular with) the tricuspid valve annulus (Supplemental Figure 1). In addition, these maneuvers tend to lose height across the tricuspid valve annulus and movement toward the posteroseptal commissure. Conversely, the Extend (E) or Minus (-) knobs have the opposite effects, shifting the catheter away from the tricuspid valve annulus (ie, gaining height) while moving closer to the superiorly located anteroseptal commissure.

FIGURE 11 **Catheter Manipulations Across the Chamber Views for Transcatheter Tricuspid Valve Interventions**



This figure illustrates the significance of the 1C, 3C, and 4C views in guiding intentional catheter manipulations. The 1C and 3C views are utilized for push/pull maneuvers, in which pushing a catheter from the femoral approach moves it superiorly toward the anteroseptal commissure, while pulling the catheter moves it inferiorly toward the posteroseptal commissure. The 1C and 4C views are utilized for clockwise/counterclockwise movements, in which clockwise moves the catheter posteriorly toward the septal leaflet and counterclockwise moves it anteriorly toward the anterior leaflet. (I) The green panel represents the 1C view; (II) the blue panel represents the 3C view (multidetector computed tomography [MDCT], fluoroscopy, and midesophageal transesophageal echocardiography [TEE]); and (III) the orange panel represents the 4C view (MDCT, fluoroscopy, and midesophageal TEE). In all 3 panels, the anterior leaflet is represented by a dotted yellow line, the posterior leaflet by a continuous green line, and the septal leaflet by a continuous pink line. Catheter movements are indicated by orange (clockwise/counterclockwise rotation) and blue (push and pull movements) arrows. Abbreviations as in Figure 3.

NAVIGATING ACROSS THE 4-CHAMBER VIEW. Counterclockwise rotation in the 4-chamber view moves the catheter anteriorly toward the anterior tricuspid valve leaflet, while clockwise rotation moves the catheter posteriorly toward the septal leaflet. Using dedicated knobs, such as the lateral knob found on the TriClip system, catheters can be deflected anteriorly away from the atrial septum and toward the anterior leaflet, while the septal knob deflects catheters posteriorly toward the septal leaflet or atrial septum (**Figure 11**, Supplemental Figure 1).

INTEGRATING CHAMBER VIEWS DURING TRANSCATHETER TRICUSPID VALVE REPAIR AND REPLACEMENT PROCEDURES

Transcatheter tricuspid valve repair and replacement procedures typically require delivery systems to be perpendicular to the valvular coaptation plane to prevent oblique and misplaced implantations.[18,19] Although this is typically achieved with TEE imaging, fluoroscopy can provide additional useful guidance.

Perpendicular positioning of delivery catheters across the tricuspid valve annulus or a particular commissure can be accomplished using X-plane or multiplanar reconstructions during TEE imaging. More specifically, the 1-, 3-, and 4-chamber views are combined to “geolocate” the catheter across the plane of the tricuspid valve annulus. During transfemoral transcatheter tricuspid valve interventions, the 1-chamber view provides the inferior vena cava and atrial septum in plane while the tricuspid valve annulus is en face, the 3-chamber view provides the “3 structures” in plane, and the 4-chamber view provides the inferior vena cava en face and the atrial septum and tricuspid valve annulus in plane (**Figure 3**). These 3-chamber views (ie, 1, 3, and 4) also provide the information needed to appreciate potential anatomical variability between individual patients. With respect to positioning catheters across the plane of the tricuspid valve annulus, the 3-chamber view provides feedback concerning push-pull movements and the 4-chamber view for clockwise and counterclockwise movements (**Figure 11**, Supplemental Figure 1). In **Figure 10**, the TriClip system is positioned relatively superior in the 3-chamber view but is centered in the 4-chamber view, allowing targeting of the anteroseptal commissure.[20]

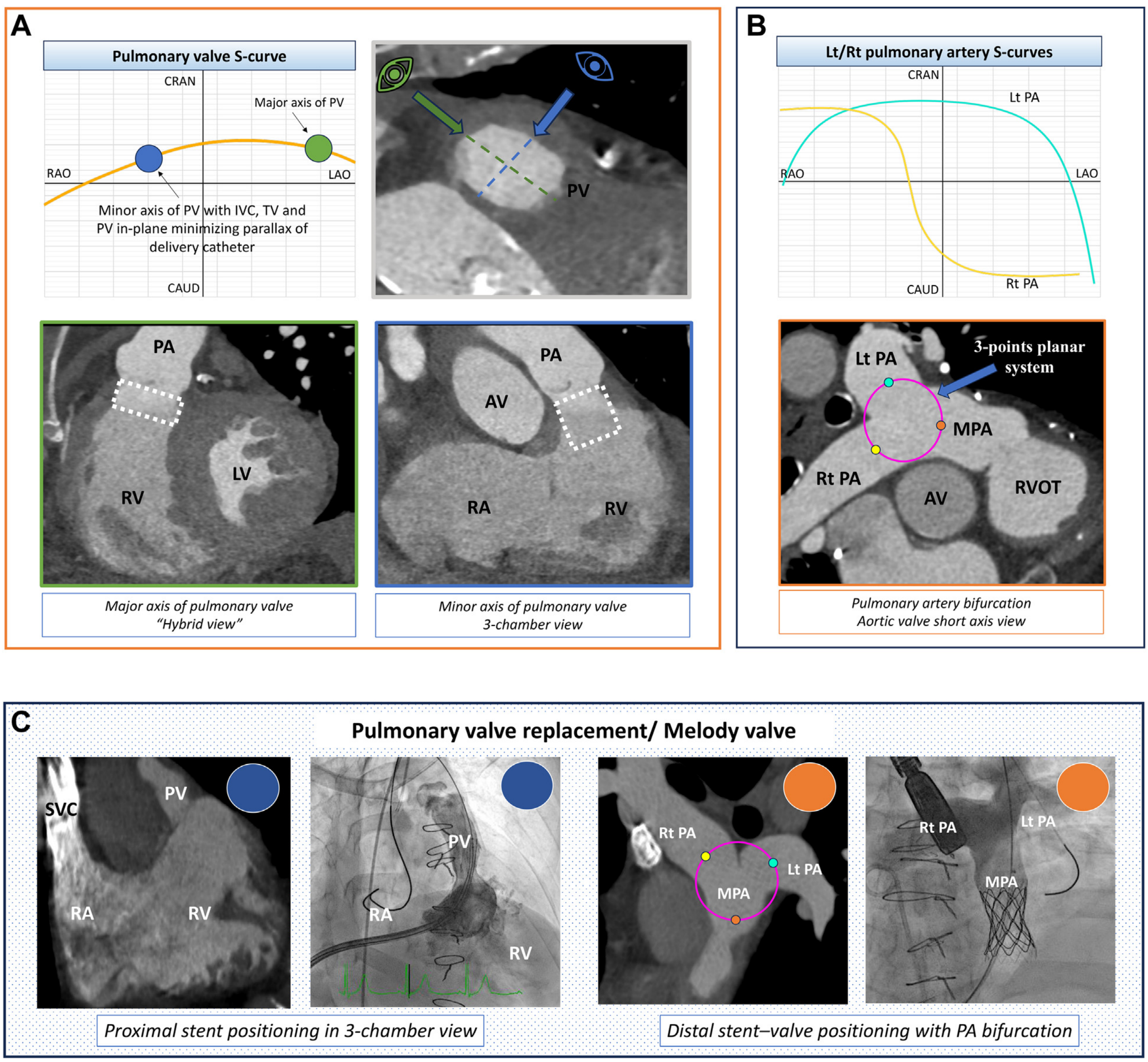
In addition to echocardiography, the fluoroscopic 1- and 3-chamber views can be helpful in achieving device coaxiality (**Figure 10**, Supplemental Figure 2). Although patient-specific MSCT-derived fluoroscopic viewing angles are optimal for this purpose, established average angles for the 1-chamber (LAO 55 CAUD 15) and 3-chamber views (RAO 25 CRAN 15) can be substituted for most patients. The delivery system should appear to travel “in and out of” the fluoroscopic screen in the 1-chamber view but running horizontal or slightly inferior (10°-15° from the horizontal) in the fluoroscopic 3-chamber view. The distance of travel from the inferior vena cava to the tricuspid valve annulus is also best appreciated in the 3-chamber view (**Figure 9**, Supplemental Figure 2).

INTEGRATING CHAMBER VIEWS DURING TRANSCATHETER PULMONARY VALVE REPLACEMENT PROCEDURES

The pulmonary valve annulus S-curve transects the RAO CAUD, RAO CRAN, and LAO CRAN quadrants and can therefore be viewed en face in LAO CAUD (**Figure 12**). Identification of 3 important anatomical landmarks is essential during transcatheter pulmonary valve implantation: 1) the main pulmonary artery, left pulmonary artery, and right pulmonary artery bifurcation, to avoid jailing the pulmonary artery branches; 2) the right ventricular outflow tract/pulmonary valve location, to avoid low implantation and consequent ventricular arrythmias; and 3) the landing zone of the transcatheter pulmonary valve and its proximity to the left main coronary artery/left anterior descending coronary artery (LAD), to assess the risk of extrinsic coronary artery compression during valve deployment.[21,22]

The right heart 3-chamber view elongates the right ventricular outflow tract into the main pulmonary artery, mitigating anatomical and delivery catheter foreshortening. It provides the optimal view for device positioning and understanding the “push-pull” mechanics of the delivery system (**Figure 8**). Although biplane imaging is typically used during transcatheter pulmonary valve replacement, it is worth questioning “traditional dogma” given accumulating experience with transcatheter valve replacement. In addition, optimal fluoroscopic views of the pulmonary artery bifurcation are essential when positioning the distal aspect of the stent/valve to avoid right or left pulmonary artery implantation. The optimal fluoroscopic angle to viewing the pulmonary artery bifurcation can be obtained using 3-point planar methodology originally established for

FIGURE 12 The Role of the 3- and "Superior" 4-Chamber Views (ie, PA Bifurcation) in PV Replacement Procedures



The 3-chamber (inflow/outflow) view (~RAO 25° CRAN 15°) demonstrates the IVC, TA, and PV all in plane, "elongates" the anatomy, and mitigates delivery catheter parallax, thereby facilitating accurate positioning of the inflow portion of the prosthesis. Similarly, the 4-chamber view (~RAO 30° CRAN 40°) highlights the main pulmonary artery (PA) bifurcation. (A) PV S-curve (continuous orange line); the major and minor PV axis are obtained in hybrid and 3-chamber views, respectively. (B) Optimal fluoroscopic projection of the left PA (continuous teal line), right PA (continuous yellow line), and PA bifurcation/aortic valve in short axis (orange panel), in which the optimal view of the PA bifurcation is obtained by a 3-point planar system. (C) PV replacement with the Melody valve utilizing the 3-chamber and pulmonary bifurcation views. AV = aortic valve; Rt = right; Lt = left; MPA = main pulmonary artery; RVOT = right ventricular outflow tract; other abbreviations as in Figures 1, 6, and 8.

coronary artery bifurcations.[23] Although the optimal viewing angle is often extreme RAO CRAN, use of a more standard (albeit suboptimal) viewing angle (eg, RAO 30° CRAN 35°) can be both practical and technically useful.

In summary, the proximal and distal aspects of the stent/valve can be positioned using a shallow and steep RAO CRAN, respectively (eg, RAO 30° CRAN 5° and RAO 30° CRAN 35°) (Figure 12). An extreme LAO projection (40°-80°) normally avoids overlap and

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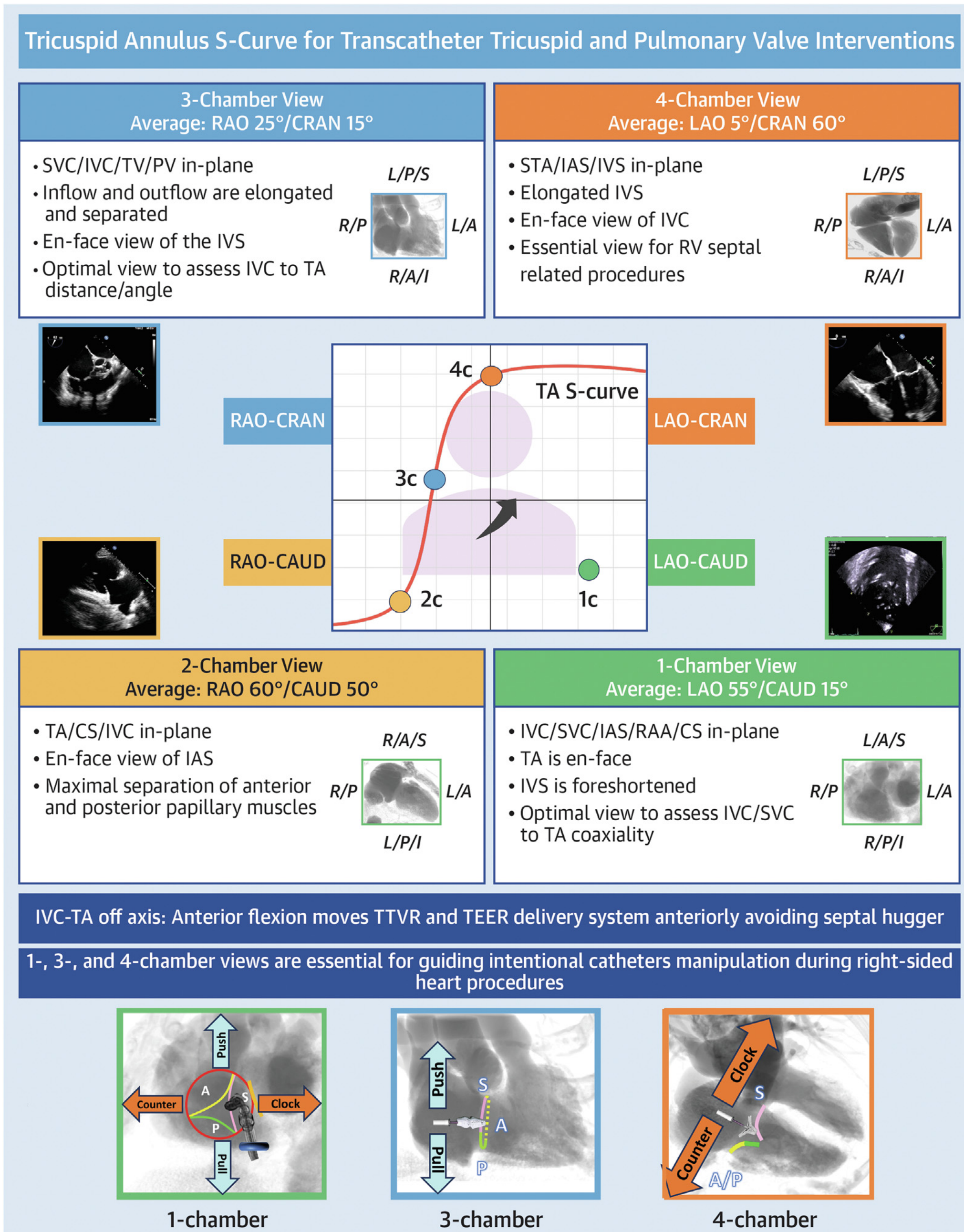
CENTRAL ILLUSTRATION S-Curves and Chamber Views for Right-Sided Heart Valve Procedures



Zgheib A, et al. JACC Cardiovasc Interv. 2024;17(23):2713-2731.

The interrelation of multimodality imaging and catheter movements across the right heart according to chamber views, S-curves, and attitudinal orientation of right heart structures. 1C = 1-chamber; 2C = 2-chamber; 3C = 3-chamber; 4C = 4-chamber; A = anterior; CAUD = caudal; CRAN = cranial; CS = coronary sinus; I = inferior; IAS = interatrial septum; IVC = inferior vena cava; IVS = interventricular septum; L = left; LAO = left anterior oblique; PV = pulmonary vein; P = posterior; R = right; RAA = right atrial appendage; RAO = right anterior oblique; RV = right ventricular; S = superior; SVC = superior vena cava; TA = tricuspid annulus; TEER = transcatheter edge-to-edge repair; TTVR = transcatheter tricuspid valve replacement; TV = tricuspid valve.

mitigates foreshortening between the main pulmonary artery and proximal LAD and is therefore the optimal view to assess potential LAD compression. The risk of coronary artery obstruction can also be assessed through sequential balloon dilation and angiography prior to stent/valve implantation.

CONCLUSIONS

This review discusses integrating echocardiography and fluoroscopy for guiding transcatheter right heart interventions. It focuses on: 1) obtaining S-curves and optimal chamber views; 2) using attitudinal descriptors (anterior/posterior, right/left, superior/inferior) for chamber views; 3) describing the tricuspid valve's anatomical relationship to surrounding structures; and 4) applying this knowledge to various right-sided cardiac interventions (**Central Illustration**).

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KEY WORDS chamber views, multimodality imaging, optimal projection curve, transcatheter tricuspid valve interventions

APPENDIX For supplemental figures and a video of the interactive Central Illustration, please see the online version of the paper.