INTRODUCTION

The imaging of tricuspid valve disease has been investigated less than that of left-sided valve disease, largely because of the late onset of symptoms and the difficulty in image acquisition. Interest in the tricuspid valve has increased over the past two decades after recognition of the prognostic implications of functional tricuspid regurgitation (TR) [1,2] and the introduction of the transcatheter approach to the tricuspid valve. The role of imaging modalities in assessing the extent of TR and selecting appropriate candidates for transcatheter treatment has become increasingly important.

Right ventricle (RV) function analysis plays an important role in evaluating the pathogenesis, diagnosis, and prognosis of cardiopulmonary diseases, including congestive heart failure, pulmonary hypertension, and pulmonary embolism [3,4]. Although transthoracic echocardiography (TTE) is a first-line imaging modality for analyzing ventricular function, it is limited because the RV has a thin wall with heavy trabeculation, which makes it difficult to delineate. Cardiac magnetic resonance imaging (CMR) is considered the gold standard for volumetric quantification of the RV, as it provides excellent endocardial definition, and enables quantitative measurement of TR using phase-contrast images. Cardiac computed tomography (CT) and CMR have enabled a more comprehensive understanding of the tricuspid valve. In this article, we review the anatomy of the tricuspid valve and CT and CMR protocols for the assessment of the right heart, illustrating methods for RV function and TR analyses using cardiac CT and CMR. Additionally, we demonstrate the use of cardiac CT in the planning of transcatheter treatment of TR and the evaluation of postoperative complications.
Tricuspid Valve and Right Heart Imaging Using Cardiac CT and MRI

A complex anatomy, which consists of four components: three leaflets (anterior, septal, and posterior) (Fig. 1), the fibrous annulus, the chordae tendineae, and papillary muscles. The three leaflets of the tricuspid valve vary in size and mobility; the anterior leaflet is the largest, with the longest radial length and the greatest motion. Conversely, the posterior leaflet is the smallest and has less functional significance; therefore, it can sometimes be surgically removed without impairment of valve function [5]. The septal leaflet has the shortest radial length and lowest mobility. The commissure between the anterior and septal leaflets is the longest commissure and lies on the membranous septum that divides the atrioventricular and interventricular portions [6]. The non-coronary sinus of Valsalva is located adjacent to this anteroseptal commissure and can be injured during transcatheter intervention [7]. The commissure between the septal and posterior leaflets is adjacent to the entrance of the coronary sinus into the right atrium.

Tricuspid Annulus

The tricuspid annulus is a D-shaped saddle-like non-planar structure consisting of two distinct structures: a larger C-shaped segment (the posterolateral segment of the annulus corresponding to the right atrium and RV free wall) and a relatively straight segment (the anterior-septal segment of the annulus corresponding to the septal leaflet and ventricular septum). The tricuspid annulus is a dynamic structure, and in healthy people, its orifice area undergoes changes of up to 29% from diastole to systole (Fig. 2) [8]. Its size is largest in late diastole after atrial contraction [9].

Fig. 1. CT images of the tricuspid valve.
A, B. Short-axis views toward the tricuspid valve at the right ventricular side in the systolic (35% of R-R interval) and diastolic (70% of R-R interval) phases. C. Septal and anterior tricuspid leaflets on the long-axis four-chamber view. The tricuspid annulus is located more apically than the mitral valve annulus (arrow). D. Posterior and anterior leaflets are visualized on the long-axis right two-chamber view. ATV = anterior tricuspid valve leaflet, PTV = posterior tricuspid valve leaflet, STV = septal tricuspid valve leaflet.
Subvalvular Apparatus

Two papillary muscles and a third variable papillary muscle provide tense support to the tricuspid valve leaflets (Fig. 3). Of the two papillary muscles, the anterior papillary muscle arising from the anterior RV wall is larger and provides chordal support to the anterior and posterior leaflets. The moderator band extends from the trabecular septo-marginalis, arising from the interventricular septum to the base of the anterior papillary muscle. These connections form a U-shaped complex structure, dividing the inflow and outflow portions of the RV (Fig. 3) [10]. The posterior papillary muscles arising from the inferior wall provide chordal support to the posterior and septal leaflets. The septal papillary muscle is small and is present in multiples, or may even be absent in the normal population. It arises from the conus or RV septal wall and connects the chordae to the anterior and septal leaflets. Because the two leaflets (septal and anterior) are connected to the RV septal wall, and two leaflets (anterior and posterior) are also connected to the anterior RV wall via the anterior papillary muscle, displacement of the RV septum or anterior wall affects the coaptation of the leaflets. Among the three leaflets, the septal leaflet has a characteristic chordal attachment, with direct attachment of the chorda to the septum or main medial papillary muscle, which in turn inserts into the trabecular septo-marginalis; this can contribute to tethering of leaflets when the dilated RV displaces the papillary muscle [7]. Furthermore, chordae tendinae can be an obstacle when attempting the transcatheter approach to investigate the tricuspid valve.

Adjacent Anatomy

The septal atroventricular junction is a central structure of the heart where the septal components of the atria and ventricles connect with the aortic, mitral, and tricuspid valves. This region includes the muscular atroventricular septum, membranous septum, central fibrous body, Koch triangle, and the base of the interventricular septum (Fig. 4).

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**Fig. 2. Change in the tricuspid annulus shape during the cardiac phases.** The area and perimeter of the tricuspid annulus are increased to the maximum size during diastole (yellow-dotted line). The diastolic phase image was obtained in the arterial phase by a bolus tracking method, 5–6 seconds after the ascending aorta reached 100 Hounsfield unit during a biphasic protocol. The tricuspid annulus size decreases during systole to the maximum size at end-systole (red-dotted line). The systolic phase image was obtained using a triphasic protocol.

**Fig. 3. Subvalvular apparatus.** Anterior papillary muscle (black arrows) and posterior papillary muscle (white arrows) on a long-axis right two-chamber view, short-axis view, and five-chamber views. The moderator band (black arrowheads) originates from the trabecular septo-marginalis and joins the base of the anterior papillary muscle, crossing the right ventricular cavity. This anatomy forms the U-shaped structure.
The septal leaflet of the tricuspid valve is hinged from the right side of the membranous septum and divides it into atrioventricular and interventricular components. The triangle of Koch is a part of the medial right atrial wall, which is located at the level of the inferior pyramidal space. It contains the atrioventricular node and is therefore an important site for catheter ablation [12].

**Anatomic Considerations for Transcatheter Tricuspid Valve Therapy**

There are several anatomic features that must be considered before transcatheter tricuspid valve therapy. First, the right coronary artery (RCA) courses adjacent to the tricuspid annulus on the anterolateral side of the annulus, which has the anatomic goal of annular reduction, and cardiogenic shock secondary to direct injury to the RCA can occur. Injury to the atrioventricular node located within the triangle of Koch, adjacent to the tricuspid annulus, can also cause conduction disturbances. In addition, the fibrous annulus makes it difficult to anchor the device effectively. Furthermore, the transcatheter approach is difficult in a highly dilated annulus without calcification, as may be present in patients with the most severe TR. Finally, patients with pacemakers or cardiac implantable electronic devices in situ can present limitations in the insertion of devices [13].

**Types of Tricuspid Regurgitation**

TR can be divided into two types, primary and secondary, according to their pathophysiology. Primary TR results from a primitive lesion in the tricuspid valve, which may be the result of a congenital anomaly (e.g., Ebstein's...
anomaly) or an acquired disease (e.g., rheumatic disease, endocarditis, or myxomatous degeneration). Primary TR is rare and should be distinguished from secondary TR for appropriate clinical management [7]. Secondary (functional) TR is the most common form, resulting from morphological abnormalities in the RV and tricuspid apparatus: tethering or tenting of the leaflet, tricuspid annular dilatation, or malcoaptation caused by RV dilatation and dysfunction [14]. The underlying disease can be further classified into four categories as follows [7]: 1) left-sided heart disease, such as mitral valve disease or LV dysfunction, 2) pulmonary arterial hypertension, 3) conditions resulting from RV dysfunction, such as myocardial infarction/ischemia, and 4) idiopathic TR with no detectable cause.

CT Imaging Techniques and Analyses

Cardiac CT Protocol for Right Heart Evaluation

Clear visualization of the right atrioventricular junction is challenging. The contrast media injection protocol for visualization of the right heart structures on cardiac CT differs from that used for left heart visualization. In conventional routine coronary CT angiography using the bolus tracking method, scanning is started 5–6 seconds after the ascending aorta reaches 100–140 Hounsfield unit (HU), which causes heterogeneous attenuation of the right-side heart with a mix of contrast agent and blood [15]. Therefore, a modified protocol is needed, which involves using a 50% dose of contrast media (1:1 mixture of contrast media and saline) and saline chasing; and provides homogeneous attenuation of the RV cavity and outlet [5]. In our hospital, RV imaging is performed using a triphasic protocol that involves the injection of 60–65 mL contrast media, 20 mL of 70:30 saline-contrast mixture, and 40 mL saline chaser. However, this is sometimes insufficient for evaluation of the RV inlet and tricuspid valve because of inhomogeneous enhancement of the right atrium, and streak artifacts when contrast media in the superior vena cava mixes with unenhanced blood from the inferior vena cava [5]. To prevent this problem, a semi-invasive technique that simultaneously injects contrast agents via both the femoral and antecubital veins has been suggested [16]. This is an ideal method, but due to its invasiveness, the biphasic or triphasic protocol is generally used [17,18]. For function analysis with electrocardiography (ECG)-gated cardiac CT, multiphase data with a maximum 1.5-mm slice thickness reconstructed for at least 10 phases of the cardiac cycle (0%–90% of R-R interval) are required. A relatively high radiation dose is inevitable during multiphase cardiac-gated acquisition for the evaluation of ventricular function or dynamic motion of the heart valves. To reduce this radiation dose, ECG-controlled tube current modulation or wide-detector CT are options that are worthy of consideration [19,20]. Low-dose scanning with iterative reconstruction is another option for obtaining multiphase data with reduced radiation doses [21,22].

CT Image Reconstruction

To measure the tricuspid annulus on cardiac CT, it is recommended to use a reconstructed short-axis image with manual selection of the level of the plane at an annulus level on four-chamber and two-chamber images acquired at end-diastole (Fig. 5). The normal maximum annulus diameter, circumference, and area are 3.1 ± 0.4 cm, 11.9 ± 0.9 cm, and 11.3 ± 1.8 cm², respectively, on the four-chamber view of two-dimensional (2D) echocardiography [23,24], and 3.0–3.5 cm on the short-axis CT image [18]. In functional TR, which is characterized by a dilated annulus (> 40 mm) [25], the annulus dilates along the RV free wall, and the shape becomes more circular and flatter (Fig. 6) [26].

The four-chamber view of cardiac CT allows delineation of the location of the tricuspid leaflets and the three commissures. The septal leaflet directly arises from the medial side of the tricuspid annulus, above the interventricular septum, and ≤ 10 mm apical to the septal insertion of the anterior leaflet of the mitral valve (Fig. 1).

Fig. 5. Measurement of the tricuspid annulus on cardiac CT. The perimeter (red-dotted line) and diameters (yellow lines) are measured on a reconstructed short-axis view by manually adjusting the plane level at the tricuspid annulus on the long-axis four-chamber (top box) and the long-axis two-chamber views (bottom box).
The muscular atrioventricular septum is located in the difference in the level of attachment of the tricuspid and mitral valves. The coaptation of leaflets occurs at the level of the annulus or just below the annulus, with a coaptation length of 5–10 mm [14]. The anterior and posterior tricuspid leaflets can be visualized on the right heart two-chamber view. The planning of transcatheter tricuspid valve therapy is based on four- and two-chamber CT views, and is discussed later in this review.

The normal RV free wall thickness is < 4 mm in a four-chamber view during diastole [27]. Chronic pressure overload in congenital heart disease, pulmonary hypertension, pulmonary valve stenosis, or RV outflow tract obstruction, causes RV hypertrophy. Because RV hypertrophy gradually progresses, it can help distinguish acute from chronic pulmonary embolism [28].

**Right Ventricular Function Analysis Using CT**
Cardiac CT has good accuracy and reproducibility for RV function analysis when compared to CMR as a reference method [4]. The advantages and disadvantages of cardiac CT and CMR are summarized in Table 1, and the normal RV parameters are summarized in Table 2 [29,30].

![Fig. 6. Change in the tricuspid annulus in functional TR.](image)

Normally, the tricuspid annulus is a non-planar saddle-like stricture. As the right heart function deteriorates, the annulus dilates toward the anteroposterior direction, and the shape becomes more planar and circular (illustration). Two CT images of a 77-year-old female who underwent mitral valve replacement and had functional TR with right heart enlargement. The coaptation defect of the tricuspid valve occurs during the systolic phase (arrowhead). The tricuspid annulus is large and circular on the reconstructed short-axis view. ATV = anterior tricuspid valve leaflet, AV = atrioventricular, PTV = posterior tricuspid valve leaflet, STV = septal tricuspid valve leaflet, TR = tricuspid regurgitation

| Table 1. Pros and Cons of Cardiac CT and MRI |
|---------------------------------------------|
| **Cardiac CT**                               | **CMR**                             |
| Pros                                        |                                     |
| Good accuracy and reproducibility with CMR  | The gold standard for RV volumetric quantification |
| as the reference standard                    | High temporal resolution             |
| Useful in complex adult congenital heart disease patients with cardiac devices | Excellent endocardial definition |
| Short total scan time (time saving)         | Regional wall motion abnormalities and tissue characterization |
|                                             | Accurate and reproducible right heart volume measurement |
|                                             | Quantitative measurement of TR with phase-contrast imaging |
| Cons                                        |                                     |
| Limited tissue evaluation                   | High cost                            |
| Ionizing radiation                          | Long total scan time                 |
| Metallic artifacts                          | Relative contraindication if a metallic device is present (metallic artifacts exist even if CMR can be obtained) |

CMR = cardiac magnetic resonance imaging, RV = right ventricle, TR = tricuspid regurgitation
The multiplanar reformatted image in the short-axis view was used for RV function analysis and mass measurement. The early signs of RV volume or pressure overload manifest as RV size alteration and can be assessed using the RV dimension and volume [31]. For volumetric measurement, the endocardial border is traced along the axis of the base to the apex. Both papillary muscles and trabeculations are generally incorporated into the RV cavity by manual contour tracing. These structures can be excluded from the volume quantification in a semiautomatic contouring method using attenuation threshold-based selection (Fig. 7). RV endocardial borders are segmented at end-diastole (the first image after the R-wave based on ECG, which gives the maximal cross-sectional area on short-axis cine images and with the largest RV blood volume) and end-systole (cardiac phase with minimal cross-sectional area at the same level) [32,33]. RV volumes were calculated by applying Simpson’s method (an interpolated summation of stack of disks).

Assessment of TR with Cardiac CT

Compared to echocardiography and CMR, the quantification of TR using cardiac CT has not been systematically established. CT can be considered as an alternative modality only in patients with a suboptimal transthoracic echocardiographic window.

For the quantification of TR, tricuspid regurgitant volumes can be measured as the difference between the RV stroke volume and the LV stroke volume [34]. The anatomic regurgitant orifice area during mid-to-end-systole (20%–30% of the R-R interval), the tricuspid annulus area during mid-to-end-diastole (60%–80% of the R-R interval), and the tricuspid leaflet tethering area and height can be used to grade the severity of TR (Fig. 8) [35]. The regurgitant orifice area is the narrowest of the regurgitant orifice bordered by the tricuspid leaflet tips in the reformatted short-axis view. The tethering heights and area were measured on two- or four-chamber views by measuring the distance from the annular plane to the coaptation point and

![End systole and end diastole](image1)

![Volume-rendered images](image2)

**Fig. 7. Cardiac CT for RV function analysis.**

A. Short-axis images with RV cavity selection using a semiautomatic contouring method with attenuation threshold-based selection in end-systole and end-diastole. The myocardial trabeculation and papillary muscles are excluded from the volume quantification. B. Volume-rendered images of the RV cavity can be generated to quantify the RV volume. RV = right ventricle

![Regurgitant orifice area](image3)

![Tethering height and area](image4)

**Fig. 8. An 63-year-old female with severe functional tricuspid regurgitation.** Multiplanar reconstructed images were obtained at the end-systolic phase (30% of R-R interval).

A. The regurgitant orifice area is traced on the short-axis image with a yellow dashed line. B. The tricuspid tethering height (red solid line) and area (blue solid line) are measured on the long-axis right two-chamber and four-chamber images tracing the leaflets from the annular plane (red dotted line).
tracing the annular plane to the leaflets. The dimensions of the tricuspid annulus and tethering heights measured on CT correlated with the severity of TR and the prognosis of cardiovascular events in patients with moderate to severe TR [36,37]. Tethering height and area are predictors of recurrent TR in tricuspid annuloplasty [36,38], and tethering height measured on preoperative cardiac CT was an independent risk factor for postoperative recurrent TR, with a tethering height > 7.2 mm used as a cut-off value for recurrent TR after tricuspid annuloplasty (sensitivity, 72%; specificity, 100%) [36].

**CMR Imaging Techniques and Analyses**

**CMR Protocol for Right Heart Evaluation**

For volume and function analyses, the cine steady-state free-precession (SSFP) sequence with a temporal resolution < 45 ms/phase enabled the best assessment. The short-axis image should provide coverage from the base to the apex, with a slice thickness of 6–8 mm and a 2–4 mm interslice gap. The basal slice should be placed immediately on the myocardial side of the RV, and the atrial volume should be carefully removed from the basal slice at the end of systole [39]. In addition to the routinely acquired four-chamber RV long-axis view, other specialized views (RV two-chamber view, RV three-chamber view, and RV outflow tract view) should be obtained for RV and tricuspid valve evaluation, the relative orientations of which are shown in Figure 9.

**Right Ventricular Function Analysis Using CMR**

Similar to the function analysis on cardiac CT performed by tracing the endocardial margin, volumetric measurements were performed using Simpson’s method. The end-systolic and end-diastolic phases were manually selected by identifying the minimum and maximum RV volumes. Post-processing software enables an accurate short-axis slice position with reference to the long-axis view and can be used to calculate the RV volume and mass (Fig. 10). The RV mass is obtained by tracing both the epicardial and endocardial borders, usually excluding the papillary muscles [17]. To interpret the CMR for RV functional assessment, qualitative assessment, including wall motion evaluation (pattern [global/septal/free wall] and extent [normal/hypokinetic/dyskinetic]), presence of hemodynamic...
interaction between RV and LV (e.g., the reaction of ventricular interdependence in constrictive pericarditis), RV wall thickness, and presence of RV dilatation can be evaluated. For quantitative assessment, the ejection fraction (%), end-diastolic, end-systolic, stroke volume (mL and mL/m² for a body surface area-indexed value), cardiac output (L/min), and cardiac index (L/min/m²) of the RV can be measured [40].

Assessment of TR with CMR

Visualization of the RV and TR with good temporal and spatial resolution and without exposing the patient to ionizing radiation or intravenous contrast media is a major advantage of CMR. Reformatted multiplanar images enable the assessment and measurement of the tricuspid valve. On the cine SSFP image, TR can be qualitatively assessed by identifying the area of the signal drop due to turbulent flow and/or acceleration (Fig. 11). Spoiled gradient-recalled echo cine images, which have longer repetition and echo times, are also used for TR visualization when the flow void is not clearly shown on SSFP images [35]. However, this area of the signal void is affected by the echo time and windowing [41]. In addition, a higher magnetic field results in more prominent flow voids [35]. These factors should be considered before the assessment of TR to limit standardization difficulties. Although CMR enables the quantitative assessment of TR, not all MRI-specific cut-off values for the measurements have been established. The quantitative noninvasive imaging parameters that can be acquired using CMR and echocardiography are presented in Table 3 [5]. The cut-off values for severity grading were based mainly on the echocardiographic standards. For the TR fraction, recent guidelines suggest using the same severity cut-off used for mitral regurgitation (a regurgitant fraction ≤ 15% for mild TR, 16%–25% for moderate TR, 26%–48% for moderately severe TR, and > 48% for severe TR) [34].

The flow through the valve was measured using phase-contrast MRI. The regurgitant volume is indirectly measured
by subtracting the main pulmonary artery forward volume from the RV systolic volume calculated using a stack of short-axis images acquired using the method described above (Fig. 12). The TR volume can also be directly measured at the orthogonal plane of the tricuspid annulus in a velocity-encoding cine image, and this technique has shown considerable reproducibility [42].

**Treatment Options for Tricuspid Valve Disease**

Tricuspid valve surgery is a definitive therapy for patients with severe symptoms that are refractory to medical treatment [43]. The main purpose of surgery is to reduce the high RV afterload by correcting left-sided valve disease and correcting the dilated tricuspid annulus by annuloplasty (tricuspid valve repair) or tricuspid valve replacement when repair is unfeasible (e.g., marked leaflet tethering, complex primary TR, or severe tricuspid stenosis) [44]. Current guidelines recommend the timing of surgical treatment for severe functional TR at the same time as left-sided surgery or RV dysfunction [45]. Because evidence for the optimal timing of surgery is still insufficient, delaying surgery until after the development of overt RV dysfunction and end organ damage contributes to worse postoperative outcomes.

![Fig. 11. Cardiac MR parameters for quantitative assessment of TR.](image)

A 67-year-old female with severe functional TR. On the cardiac cine image using a balanced steady-state free-precession sequence, the TR jet is represented as signal void. The regurgitant area, TR length, and TR (%) can be measured by delineating the signal void area. The vena contracta width is defined as the narrowest dimension of regurgitant flow adjacent to the regurgitant orifice, just before the flow expands. The dimension of the IVC is measured on the coronal cine image. The regurgitant orifice area was obtained on the short-axis cine image. IVC = inferior vena cava, TR = tricuspid regurgitation.

**Table 3. Cardiac MRI Parameters for Quantitative Assessment of TR**

| Severity | Regurgitant Area, cm² | TR Length, cm | TR, % | Vena Contracta Width, mm² | Regurgitant Orifice Area, mm² | Regurgitant Volume, mL* | RA, RV, IVC Dimensions, cm |
|----------|------------------------|---------------|-------|---------------------------|-----------------------------|-------------------------|--------------------------|
| Mild     | < 5                    | 2             | 20    | Not defined               | Not defined                 | Not defined             | Nonspecific              |
| Moderate | 6–10                   | 3–5           | 20–34 | < 6.5                     | Not defined                 | Not defined             | Nonspecific              |
| Severe   | > 10                   | > 5           | > 35  | > 7                       | > 40                        | > 45                    | IVC > 2                  |

Adapted from Saremi et al. AJR Am J Roentgenol 2015;204:W531-W542, with permission of ARRS [5]. *RV systolic volume–main pulmonary artery forward volume, †Maximum regurgitant area divided by right atrial area, ‡Smallest regurgitant flow between convergence and expansion of flow. IVC = inferior vena cava, RA = right atrium, RV = right ventricle, TR = tricuspid regurgitation.
compared to those of the mitral or aortic valve [43]. For patients with such a high operative risk, a less invasive technique is of interest as a treatment option. Recently, various transcatheter tricuspid valve therapy techniques have been developed, which have shown promising results in the clinical evaluation stage [46]. Transcatheter tricuspid valve therapy is classified as transcatheter tricuspid valve repair, transcatheter tricuspid valve replacement, and heterotopic caval valve implantation.

Types of Device and CT Planning for Transcatheter Tricuspid Valve Therapy

Transcatheter tricuspid valve therapy can be categorized based on its anatomic therapeutic target (Fig. 13). Tricuspid valve repair can be classified as repair using a coaptation or annuloplasty device, heterotopic caval valve implantation (which is performed in the superior vena cava or inferior vena cava), and orthotopic transcatheter tricuspid valve replacement (Table 4) [13]. Cardiac CT has become an important imaging modality for pre-procedural evaluation, providing geometric information on the RV and tricuspid valve annulus (which is a non-planar structure making deployment and landing of the device hard), and clarifying the relationship between the RCA and tricuspid valve annulus, which is occasionally difficult to evaluate on echocardiography [47]. The measurement parameters obtained from cardiac CT for the planning of transcatheter tricuspid valve therapy are explained below and are shown in Figure 14.

1) Tricuspid annulus dimensions and distance between

![Fig. 12. Calculation of tricuspid regurgitant volume.](image)

A 39-year-old male with severe functional tricuspid regurgitation.

A. The through-plane phase-contrast image for pulmonary flow is obtained at the level just above the pulmonary valve, and the total forward flow (red-lined box) is measured by drawing a region of interest on the main pulmonary artery (red-lined area). B. The RV stroke volume (blue-lined box) is derived from both systolic and diastolic SAX stacks from the base to apex of the RV. The regurgitant volume was calculated by subtracting the pulmonary forward volume from the RV systolic volume as follows: $94.71 - 51.10 = 43.61$ mL. BSA = body surface area, $H =$ height, HR = heart rate, $RV =$ right ventricle, RVCI = RV cardiac index, RVCO = RV cardiac output, RVEDV = RV end-diastolic volume, RVEF = RV ejection fraction, RVESV = RV end-systolic volume, RSVS = RV stroke volume, SAX = short axis

![Fig. 13. Types of transcatheter therapy for tricuspid regurgitation.](image)

A. A spacer device for improving leaflet coaptation and reducing the regurgitation orifice. B. A clipping device for direct suture annuloplasty. C. Heterotopic caval valve implanted in the inferior vena cava.
the tricuspid valve annulus and the RV apex: in a spacer system, the anchoring system is first implanted into the RV septal free-wall groove. The spacer, a foam-filled polymer balloon, is located perpendicular to the tricuspid annular plane and reduces the coaptation gap. Therefore, a maximal distance between the tricuspid valve annulus and the RV apex is required. The dimensions (diameter, perimeter, and area) of the tricuspid valve on multiplanar images should be evaluated before implanting the device (which directly interacts with the tricuspid valve leaflet) and transcatheter tricuspid valve replacement.

2) Anatomic relationship with RCA: as the RCA often courses parallel to the tricuspid annulus during the direct tricuspid annuloplasty procedure or transcatheter tricuspid valve replacement, the RCA can impinge. CT provides an accurate measurement of the distance from the tricuspid valve annulus. Measurements were performed on short-axis and four-chamber views, and the clipping site was used for direct annuloplasty at the location of the anterior and posterior leaflets. The transcatheter procedure can be precluded by an unfavorable course (RCA ≤ 2 mm from the TA). [48]. If the RCA course is below or above the tricuspid annular level and not parallel to the annulus, thick-slabbed multiplanar images and volume-rendered images can be

Table 4. Types of Transcatheter TV Therapy

| Type                | Mechanism                                                                 | Anatomical Targets and Key Measures                                                                 | Cardiac CT Images                                                                 | Device | Ongoing Study |
|---------------------|---------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------|--------|---------------|
| Annuloplasty        | Divided into direct suture (Trialign, TriCinch, MIA) or ring (Cardioband, IRIS) annuloplasty device Reduce annular diameters by plication of tissue (direct suture) or bidirectional reshaping and reduction of annulus using attached ring (ring annuloplasty) | Course of RCA and four-chamber views, Long-axis two-chamber view, and anterior/posterior TV leaflet insertion | Long-axis two-chamber and four-chamber views, volume-rendered images, and anterior/posterior TV leaflet insertion | Trialign Cardioband TriCinch IRIS MIA | SCOUT II PREVENT TRI-REPAIR STTAR |
| Annular spacer      | Polymer balloon is deployed at the TV to improve coaptation, with anchoring system implanted in the RV septal wall | Tricuspid annulus dimension: Distance from the tricuspid annulus to the RV apex | Short axis of the TV and four-chamber views, volume-rendered images | Forma | SPACER |
| CAVI (heterotopic caval valve implantation) | Prevent caval backflow of TR and reduce symptoms and signs of RV failure (systemic venous congestion) | The dimension of IVC at the levels of the cavoatrial junction and first hepatic vein Distance from the IVC to the 1st hepatic vein | Transverse plane of cavoatrial junction Oblique sagittal plane of the IVC | TricValve® SapienXT | HOVER TRICAVA |
| Valve replacement   | Implantation of self-expandable bioprosthetic TV First reported in 2014 | Tricuspid annulus dimension: Course of RCA, Distance from the tricuspid annulus to the RV apex, The right internal jugular vein and SVC size RVOT evaluation | Short axis of the TV Long-axis two-chamber and four-chamber views, volume-rendered images, and Long-axis four-chamber view | NaviGate | |

[CardioBand (Edwards Lifesciences), Forma (Edwards Lifesciences), IRIS (Millipede, Inc.), MIA (Micro Interventional Devices, Inc.), NaviGate (NaviGate Cardiac Structures, Inc.), SapienXT (Edwards Lifesciences), Trialign (MitraIign Inc.), TriCinch (4Tech Cardio Ltd.), TricValve® (P&F Products & Features). IVC = inferior vena cava, RCA = right coronary artery, RV = right ventricle, RVOT = RV outflow tract, SVC = superior vena cava, TR = tricuspid regurgitation, TV = tricuspid valve]
useful.

3) Dimensions of caval veins: the dimensions of the inferior vena cava should be measured at the levels of the cavoatrial junction and the first hepatic vein for caval valve implantation. Additionally, the distance between the cavoatrial junction and the superior hepatic vein should be measured to prevent obstruction of the hepatic vein during valve implantation. The diameter of the superior vena cava valve was measured at the superior cavoatrial junction.

Postoperative Findings after Surgical Tricuspid Valve Replacement

Prosthetic Valve Thrombosis

Although prosthetic valve thrombosis is a rare complication, it can be fatal when not properly treated [49]. The incidence of prosthetic valve thrombosis in the tricuspid valve is up to 4.55% [50], whereas it is 0.55% in the aortic or mitral valve positions [51]. In general, bioprosthetic valve thrombosis occurs within 1–2 years after valve implantation in patients with risk factors of paroxysmal atrial fibrillation or a hypercoagulable state, such as recent withdrawal of oral anticoagulation or a subtherapeutic prothrombin time [52]. The elevated incidence of tricuspid valve thrombosis is thought to result from lower pressure on the right side of the heart across the prosthetic valve compared to that on the left side of the heart. Moreover, pulmonary hypertension can cause endothelial injury in the right atrium and ventricle, subsequently increasing the susceptibility to thrombus formation [49].

Usually, an initial diagnosis of prosthetic valve dysfunction is made using TTE or transesophageal echocardiography. Doppler parameters of a continuous wave with an emptying velocity > 1.7 m/s, a mean gradient > 6 mm Hg, or a pressure half-time > 230 ms suggest obstruction of the prosthetic tricuspid valve [53]. However, echocardiography
has limited utility in the evaluation of leaflet motion due to acoustic shadowing and artifacts generated by the mechanical valve [49]. Cardiac CT has a complementary role in the assessment of prosthetic valve dysfunction by identifying thrombus formation and leaflet motion (Fig. 15) and distinguishing thrombus from pannus [54,55].

Subprosthetic Pannus Formation

Pannus is one of the main causes of prosthetic valve obstruction, with valve thrombosis restricting leaflet motion [56]. Pannus is an overgrowth of fibroblastic tissue with inflammatory cells and intervening capillary vessels in the perianular region [57]. Although it is considered a normal endocardial healing process after surgery, protrusion into the valve orifice can cause flow disturbance and consequent valve stenosis. The incidence of prosthetic valve obstruction by pannus accounts for 6.3% of left-sided prosthetic valve obstruction [58]; however, its incidence in prosthetic valves in the tricuspid position is unclear. Distinguishing pannus from valve thrombosis is crucial because of the different treatment options for the two conditions. According to the anatomical position, the pannus is usually located in the subvalvular area of the prosthetic valve ring, as a curved lesion along the valvular ring (Fig. 16). Conversely, thrombosis can be located both in the supra- and subvalvular areas, attaching to the leaflet and hinge point, and appears as an irregular hypodense mass [59]. HU measurement on cardiac CT can

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Fig. 15. Mechanical valve thrombosis. A 35-year-old male underwent tricuspid valve replacement with an On-X 31/33 mm. A, B. On cardiac CT acquired 6 years after the operation, low attenuating soft tissues (40–60 Hounsfield units) can be seen attached along the inner lumen of the prosthetic mitral valve (black arrows). C, D. An immobile posterior leaflet (white arrows) is observable on the volume-rendered profile view images during diastolic and systolic phases. The motion of the anterior leaflet was normal, with an opening angle of 79° being within the normal range. Supplementary Video 1 also demonstrates the immobile posterior leaflet on volume-rendered multiphase cardiac CT images.
help differentiate between pannus and thrombosis, with a cut-off > 145 HU predicting pannus with a sensitivity of 88% and specificity of 95% [60]. Because of its position, the mitral valve has a higher risk for pannus formation than the aortic valve, but is less commonly associated with valve obstruction than the aortic valve [61]. This may be attributable to the large annular size and lower turbulent flow in the mitral valve compared to the aortic valve [62]. Current investigations are insufficient to evaluate the complications of prosthetic tricuspid valves, such as pannus or thrombus, and future investigations are needed for clarification.

Prosthetic Valve Opening

Prosthetic valve thrombosis and pannus formation are the two main causes of prosthetic valve obstruction, and occur due to the restriction of leaflet motion [56]. ECG-gated cardiac CT can provide information on mechanical valve obstruction, enabling the evaluation of valves with nearly motion-free images, which can be reconstructed in any plane. The opening and closing angles are measured in the “in profile” projection (the view with beams parallel to both planes of the valve ring and tilting of the disc axis) and “en face” projection (view with beams parallel to the outflow tract of the valve), similar to the procedure in fluoroscopy (Fig. 16) [63]. A 3D volume-rendered image can be generated to demonstrate the motion of the prosthetic leaflets (Supplementary Movie 1). The opening angle is measured as the distance between the valve ring and the leaflets when fully opened. The normal range of the opening angle is 60°–80° for tilting disc valves and 73°–90° for bi-leaflet valves [63].

CONCLUSION

Cardiac CT and MRI can provide accurate and detailed depictions of the anatomy of the tricuspid valve and functional assessment of the RV and TR. Given the increasing number of elderly patients with comorbidities precluding surgical treatment of TR, transcatheter treatment options have emerged and are being investigated in clinical trials. To determine the treatment options for TR, a comprehensive and accurate anatomic and functional assessment by radiologists is important to facilitate appropriate patient selection and procedure guidance.

Supplement

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Supplementary Movie Legends

Movie 1. A 35-year-old male underwent tricuspid valve replacement with an On-X 31/33 mm prosthetic heart valve. The 3D volume rendered image (first scene) intuitively shows the immobile posterior leaflet against the anterior leaflet showing normal motion. The reformatted multiplanar image (second scene) also shows the immobile posterior leaflet in both profile and en-face views.

Conflicts of Interest
The authors have no potential conflicts of interest to disclose.

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Tricuspid Valve and Right Heart Imaging Using Cardiac CT and MRI

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