Chapter 1
Anatomy of the Tricuspid Valve

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Introduction

The anatomy of the tricuspid valve is complex and often variable. Gaining a thorough understanding of the development of the tricuspid valve, its distinct components, and its adjacent structures is crucial to understanding both the pathophysiology of tricuspid valve disorders and possible clinical management strategies. This chapter will review the embryology of the tricuspid valve and consider in detail the key components of the tricuspid valve itself: the tricuspid valve leaflets, the tricuspid valve annulus, and the tricuspid tensor apparatus. It will then review clinically relevant adjacent structures and implications of anatomy for tricuspid valvular intervention.

Embryology of the Tricuspid Valve

The heart begins as a primitive coiled tube that develops into a common atrioventricular (AV) canal. Initially, the right AV canal has no direct connection with the right ventricle, but expansion and remolding of the right ventricular myocardium brings it into continuity through a muscular conduit termed the "tricuspid gully," which is immediately downstream of the AV canal [1]. A ring of specialized AV myocardium surrounds the AV canal, which forms protrusions deemed endocardial

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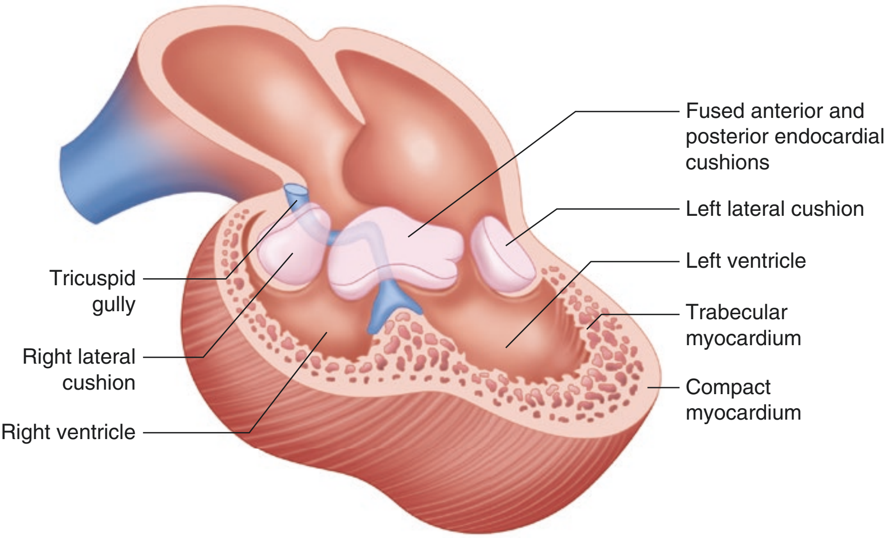

Fig. 1.1 Formation of right ventricular inlet. Right ventricular myocardium remolds and turns into the tricuspid gully, which forms the right ventricular inlet. At the same time, the AV canal cushions fuse to form the inferior septum and split the canal into two separate orifices

cushions. Endocardial cushions are loosely reticulated fibroblastic tissue masses composed of mesenchymal subendothelial tissue [2]. Myocardial protrusions form on the lateral sides of the canal, forming right and left lateral cushions, as well as on the anterior (ventral) and posterior (dorsal) walls of the AV canal, forming the anterior and posterior endocardial cushions. As the AV canal grows and straightens, the anterior and posterior cushions grow inward to begin to divide the common AV orifice into separate mitral and tricuspid orifices (Fig. 1.1).

The primitive tricuspid gully is bordered by the right lateral, posterior, and anterior cushions as well as ventricular myocardium in its inferolateral aspect [1]. The right lateral cushion forms the posterior tricuspid leaflet, and the right half of the posterior cushion forms the septal leaflet of the tricuspid valve [3]. The anterior tricuspid leaflet forms from both the right half of the anterior cushion and the right lateral cushion [1]. Tricuspid valve tissue is ultimately composed equally of endocardial cushion tissue and adjacent ventricular myocardium, with endocardial cushion tissue along the atrial aspect and myocardial tissue along the ventricular aspect, ensuring continuity with the sub-valvular tensor apparatus.

Formation of valve leaflets occurs through proliferation, extension, condensation, and delamination (Fig. 1.2) [3]. Myocardial cells immediately subendocardial to the AV cushions proliferate, which expand and extend the cushions inward. These cushions and adjacent myocardial tissue then differentiate into fibroblasts and condense into a thinner fibrous tissue. Fenestrations develop and coalesce, resulting in delamination of AV myocardial tissue from the myocardial wall in the midportion of the cushion, with attachments only in the cranial and caudal aspects. Further

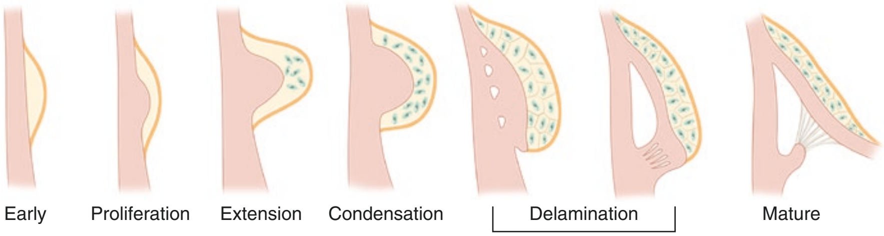

Fig. 1.2 Formation of tricuspid valve leaflets. General stages of tricuspid valve leaflet formation. Tissue in pink represents ventricular myocardium. Tissue in yellow represents endocardial cushions

fenestrations develop between structures on the caudal aspect of the cushion, creating separate papillary muscles and tendinous chordae.

The unique hemodynamics and coalescence of spaces in the ventricular trabeculated tissue during delamination in each individual may result in the creation of unique arrangements of cusps in the tricuspid valve [4], as well as pathology. For instance, Ebstein's malformation occurs from a failure of lamination of the inferior and septal leaflets from the right ventricular inlet wall [5].

A well-delineated AV junction can be seen at approximately 51 days of gestation, and by 56 days, separate AV valves are seen from the fusion of the endocardial cushions [6]. Initially, the valve leaflets are thick, but by 64 days, the leaflets become thinner and more mature in appearance.

Tricuspid Valve Leaflets

The tricuspid valve is composed of three leaflets in the majority of patients. A significant proportion of patients may have a different number of leaflets [4], though differences among studies may be confounded by the lack of a unified definition of commissures and the extent of leaflets [7]. Irrespective of the number, valve leaflets are oriented circumferentially in a curtain-like formation that separates the right atrium from the right ventricle.

The traditional three leaflets of the tricuspid valve are referred to as the anterior, posterior, and septal leaflets and are unequal in size (Fig. 1.3). The anterior leaflet is the largest in size and is oriented in an anterior-superior dimension. The anterior leaflet is the longest leaflet in a radial dimension and also has a large circumferential length along the anterior and lateral aspects of the annulus. It can occasionally contain notches that can seemingly subdivide this leaflet, though these notches do not contain the depth or fan-shaped chordal attachments characteristic of commissures between separate leaflets [7].

The posterior leaflet has a shorter radial length than the anterior leaflet and has the shortest circumferential length of all three leaflets along the posterolateral aspect of the annulus. The posterior leaflet can have multiple scallops and may not be

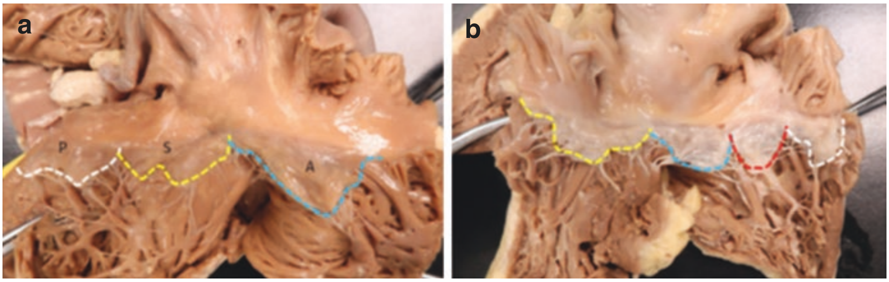

Fig. 1.3 Tricuspid valve leaflets. The number of tricuspid leaflets is highly variable. The most common configuration is a three-leaflet valve (**a**). In this figure, the white line indicates the posterior leaflet, the yellow line indicates the septal leaflet, and the blue line indicates the anterior leaflet. Frequently, more than three leaflets are seen (**b**). The orange line (**b**) represents the fourth leaflet in this quadricuspid valve. A anterior leaflet, P posterior leaflet, S septal leaflet. (Reprinted from Dahou et al. [10], Copyright (2019), with permission from Elsevier)

clearly separated from the anterior leaflet in all patients, calling for some to advocate for the classification of the anterior and posterior leaflets together as a single "mural leaflet," with multiple scallops [8], albeit with multiple zones of apposition during coaptation [9]. The commissure between the anterior and posterior leaflets is typically delineated by the insertion of a fan-shaped chorda near the acute margin of the right ventricle [7].

The septal leaflet is the shortest in the radial dimension and has the largest circumferential length along the straight portion of the annulus, immediately superior to the interventricular septum. These characteristics make it the least mobile among the three leaflets. The septal leaflet does not have any scallops, though it can have notches. The commissure between the anterior and septal leaflets is typically adjacent to the noncoronary sinus of Valsalva in the aortic root, and the commissure between the posterior and septal leaflets is adjacent to the orifice of the coronary sinus in the right atrium [10]. The insertion point of the septal tricuspid leaflet along the right ventricular aspect of the interventricular septum is displaced apically relative to the insertion point of anterior mitral leaflet along the left ventricular aspect of the interventricular septum.

Each tricuspid valve leaflet has a basal zone, rough zone, and clear zone, similar to the mitral valve [7]. The basal zone of the tricuspid leaflet extends 2–3 mm into the leaflet from the annulus and extends onto the commissural areas. The rough zone of the tricuspid leaflets is rough, thick, and semi-opaque and is the location of insertion of most chordae tendinae. The clear zone falls between the rough and basal zones.

The coaptation of the tricuspid valve is complex, with multiple coaptation zones between pairs of leaflets. There is excess coaptation length that can serve as a reserve to accommodate some annular dilation prior to malcoaptation [10]. Because the anterior and septal leaflets have the longest circumferential dimensions, they have the longest coaptation zone. It is along this zone that the majority of tricuspid regurgitation occurs.

Tricuspid Valve Annulus

The tricuspid valve annulus is the largest among the four heart valves, with an orifice area between 7 and 9 cm^2 on average [11]. The tricuspid annulus can change in size dramatically during the cardiac cycle, with the ability to increase its area by 30% [12]. The tricuspid annular area follows a biphasic pattern during the cardiac cycle, with the largest size in late diastole and an additional peak in size in early diastole, though this latter peak often disappears in patients with tricuspid regurgitation.

The tricuspid valve annulus is D-shaped with a straight portion along the interventricular septum and a curved portion along the anterior, posterior, and lateral aspects (Fig. 1.4). As the right ventricle becomes more dilated in secondary tricuspid regurgitation, the annulus dilates toward the free wall since the septal aspect of the annulus is bound by the fibrous skeleton of the heart. It is because of this property that the septal dimension can be used for annuloplasty sizing [13].

The tricuspid annular plane is oriented vertically at approximately a 45° angle from the coronal and sagittal planes, though it is typically not planar. The anteroseptal and posterolateral aspects of the annulus are more atrial, whereas the posteroseptal and anterolateral aspects of the annulus are more ventricular (Fig. 1.5) [12]. However, as tricuspid regurgitation increases in severity, the annular shape becomes more planar in the vertical dimension.

The tricuspid annulus itself is essentially a confluence of tricuspid valve leaflet hinge lines composed of fibro-adipose tissue that electrically insulates the right atrium from the right ventricle [14]. The annulus does not contain much fibrous tissue and there is no fibrous continuity with the corresponding sided semilunar valve [15]; these factors make this distinct from the mitral valve annulus. Histologically, connective tissue in a leaflet joins the subendocardial tissue or unites with a small mass of connective tissue in the ventricle [7]. On the septal aspect, leaflet connective tissue merges directly with a membranous interventricular septum.

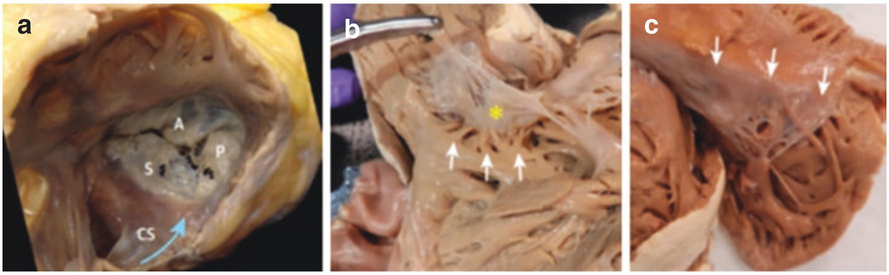

Fig. 1.4 Tricuspid valve annulus. (**a**) The tricuspid valve is seen from the atrial side with the typically D-shaped annulus composed of a flat septal region and curved anterior and posterior regions. (**b**) The ventricular surface of the anterior leaflet (asterisk) with multiple crisscrossing muscle attachments (arrows) directly to the base of the leaflet. (**c**) The atrial surface of the anterior leaflet annulus (white arrows), which is not fibrous and has a smooth transition from atrium to ventricle. CS coronary sinus (curved blue arrow), A anterior leaflet, P posterior leaflet, S septal leaflet. (Reprinted from Dahou et al. [10], Copyright (2019), with permission from Elsevier)

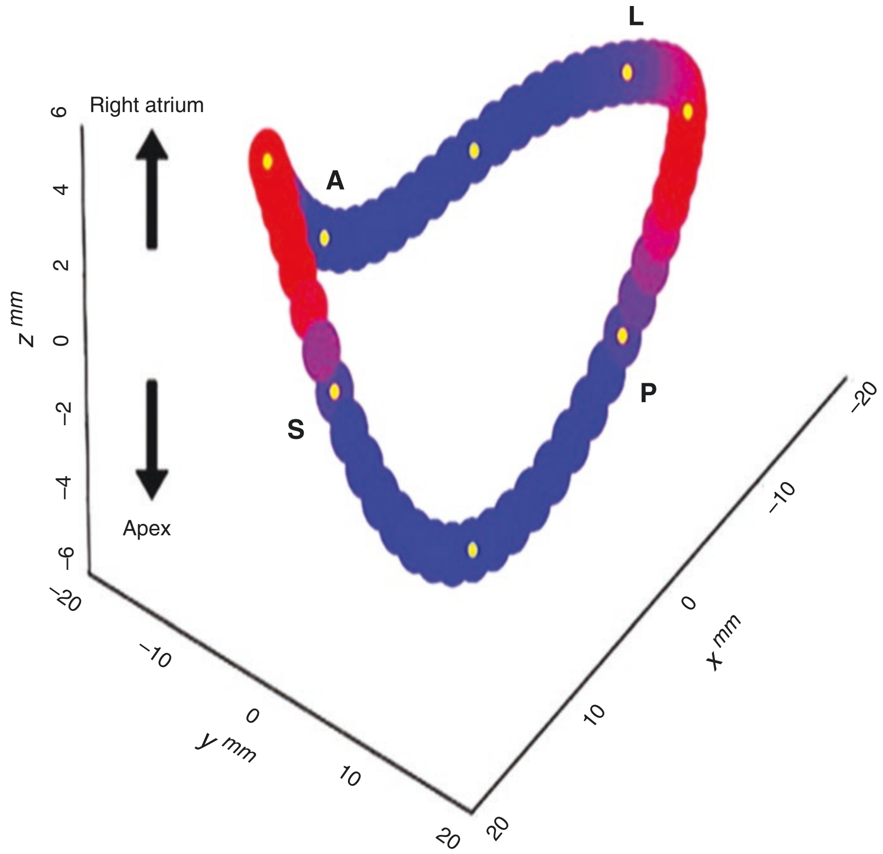

Fig. 1.5 The reconstructed ring shape for tricuspid annuloplasty, based on the average results obtained in healthy subjects at the time of minimum TA area. The positive x–y–z axis indicates the respective directions toward the septum, the posterior wall, and the right atrium. At the yellow dot, the average of each of the manually selected TA locations is shown. The reconstructed TA locations were color coded by assigning shades of red to points located above the best-fit plane toward the atrium and shades of blue to points located below the best-fit plane toward the apex. A anterior, L lateral, P posterior, S septum. (Reprinted from Fukuda et al. [12], Copyright (2006), with permission from Wolters Kluwer Health)

Tricuspid Tensor Apparatus

The tricuspid valve is attached to the right ventricle via papillary muscles and chordae that together comprise the tensor apparatus of the tricuspid valve (Fig. 1.6). Attachments of the valve leaflet tissue can vary along a spectrum from connection with a large, discrete papillary muscle to connection with a small, rudimentary papillary muscle to connect directly with the right ventricular wall.

There are typically three major papillary muscles, though this number can vary greatly [4, 14, 16]. The anterior papillary muscle is the largest and attaches to both

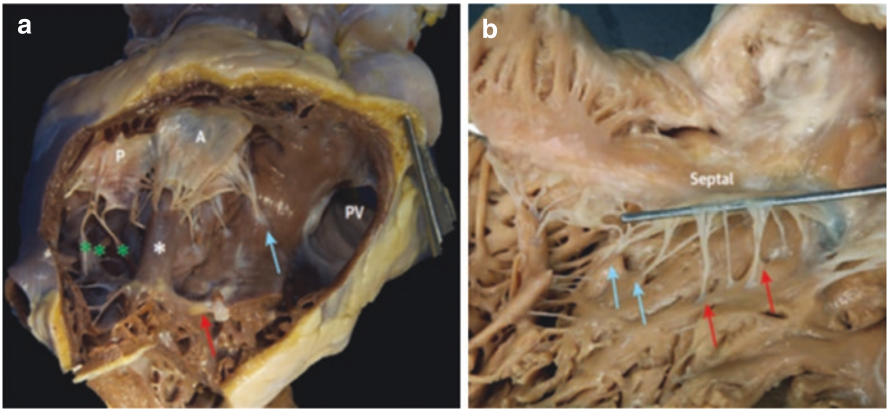

Fig. 1.6 Tricuspid valve tensor apparatus. (**a**) Typical papillary muscle distribution for the tricuspid valve. The anterior papillary muscle is typically the target (white asterisk), which provides chordal support for the A and P leaflets. The moderator band (orange arrows) may join this papillary muscle. The posterior papillary muscle is often bifid or trifid (green asterisks) and lends chordal support to the posterior and septal leaflets. The septal papillary muscle is variable (blue arrows). (**b**) Septal leaflet chordal attachments to the septal papillary muscle are shown (blue arrows) and directly from the septal myocardium (orange arrows). A anterior leaflet, P posterior leaflet. (Reprinted from Dahou et al. [10], Copyright (2019), with permission from Elsevier)

the anterior and posterior leaflets. The anterior papillary muscle can be bifid or be multiple in some cases. The posterior papillary muscle often has multiple heads and attaches to the septal and posterior leaflets. A septal papillary muscle is rudimentary and may be absent or multiple in many cases.

Chordae connect valve leaflets to the papillary muscles and typically arise from the apical third of the papillary muscle and branch soon after their origin. Accessory chordae can also connect directly from leaflet tissue to the right ventricular free wall, the interventricular septum, or the moderator band. Chordae that do not attach to leaflet tissue (“false chordae”) also exist and can connect different points on ventricular walls or papillary muscles.

There are five distinct types of chordae of the tricuspid valve: fan-shaped, rough zone, basal, free edge, and deep chordae [7]. Fan-shaped chordae insert into the commissures between leaflets and into clefts in the posterior leaflet and may have threadlike communications between their branches in a lace-like pattern. Rough zone chordae split into three branches soon after their origin and insert into the rough zone on each leaflet: one branch on the free margin of each leaflet, one branch on the line of closure, and a third branch between the two. Basal chordae are directly attached to the ventricular wall. Free edge and deep chordae are unique to the tricuspid valve. Free edge chordae are often long and form a delta-shaped insertion into a leaflet’s free edge. Deep chordae are also long and pass deep to the leaflet’s free margin inserting in the upper part of the rough zone or the clear zone, providing a second layer of chordal attachment.

The number of chordae can vary significantly, ranging from 17 to 36 in one study [7]. Tricuspid valve chordae are composed of 80% collagen organized in straight bundles and networks of fibrils, which have less extensibility than chordae of the mitral valve [17].

Adjacent Structures

Knowledge of the anatomy of structures adjacent to the tricuspid valve can give one a better understanding of tricuspid valvular pathologies as well as potential therapeutic options (Fig. 1.7).

The noncoronary sinus of Valsalva is a particularly important clinical landmark that lies immediately adjacent to the tricuspid valve annulus and marks the commissure of the anterior and septal leaflets. Additionally, the opening of the coronary sinus lies just superior to the tricuspid valve annulus and marks the commissure of the posterior and septal tricuspid valve leaflets.

The AV node and the bundle of His are also clinically relevant structures adjacent to the tricuspid valve. The bundle of His crosses the septal leaflet attachment 3–5 mm posterior to the commissure of the anterior and septal leaflets [10]. Cavo-tricuspid isthmus is another electrically important area of slow conduction that is anteromedial to the inferior vena cava and posterolateral to the tricuspid valve [18].

The right coronary artery is also adjacent to the tricuspid valve. The right coronary artery courses through the AV groove, which approximates the location of the tricuspid valve anulus. However, the right coronary artery begins its course relatively distant from the annulus and gradually becomes closer to the endocardium as it progresses. The right coronary artery runs particularly close to the annulus in the inferior segment where it lies <3 mm from the endocardial surface [19].

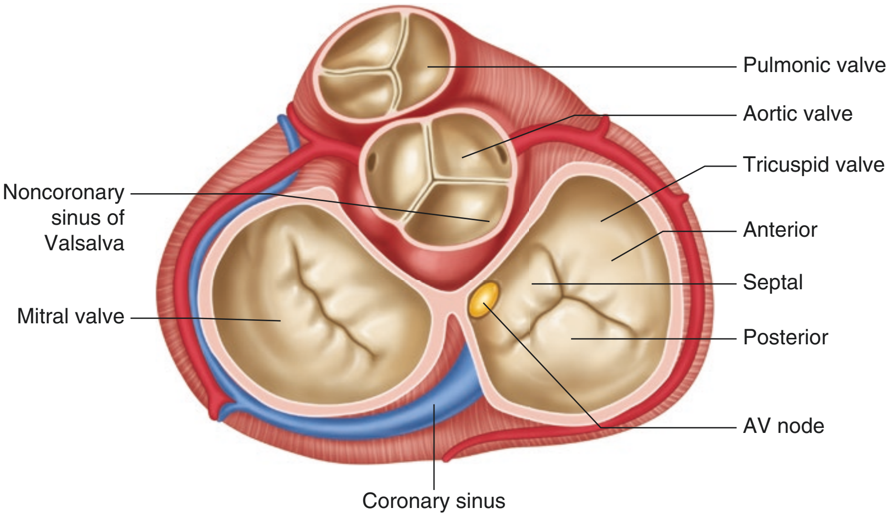

Fig. 1.7 Structures adjacent to the tricuspid valve

The venae cavae feed the right atrium and are also important structures with respect to the tricuspid valve. The inferior vena cava is formed from the confluence of the right and left common iliac veins in the retroperitoneal space and runs along the right side of the vertebral column. The superior vena cava is formed from the confluence of the right and left brachiocephalic veins and courses along the right middle mediastinum.

Implications for Tricuspid Valve Intervention

Many of the key features of tricuspid valve anatomy detailed above are important when considering surgical or transcatheter intervention to treat tricuspid valve pathology, particularly in comparison to mitral valve anatomy and intervention.

The anterior location of the tricuspid valve in the heart can make imaging guidance for procedures with transesophageal echocardiography challenging. In some cases, transthoracic echocardiography or intracardiac echocardiography may be an appropriate adjunct or substitute to obtain adequate image quality [20].

The tricuspid valve leaflets have unique features that make tricuspid valve intervention challenging. The leaflets themselves are thinner compared to the mitral valve, which makes it difficult to anchor devices to them and can make the leaflets easier to damage during manipulation. In particular, this can become an important issue with transcatheter leaflet gripping systems to address tricuspid regurgitation where tearing of the leaflets may make regurgitation worse.

The tricuspid annulus also has unique features that can make tricuspid valve intervention difficult. First, the lack of a definitive fibrous annulus or annular calcification makes it difficult to locate the annulus fluoroscopically and to seat a valve completely in the annulus. Second, the complex three-dimensional shape of the annulus can make it challenging to create annuloplasty devices that mimic a normal anatomic tricuspid annulus. Third, the larger orifice of the tricuspid valve relative to the mitral valve makes it challenging to overcome a large coaptation gap, and residual regurgitation may remain. Finally, annular devices must be designed to account for the wide variation in annular size during the cardiac cycle [10].

The complex and variable tricuspid tensor apparatus also presents unique challenges for tricuspid intervention. The multiplicity of chordae can make it challenging to manipulate transcatheter devices. This is particularly relevant for devices that attempt to attach to leaflet tips, where the majority of chordae insert. The risk of impingement of chordae is high and can lead to difficulty in device retrieval or chordal rupture and subsequent worsening of tricuspid regurgitation. Tricuspid chordal tissue is also thinner compared to the mitral valve and may be easier to damage. Finally, the presence of false chordae, which connect two spots on ventricular walls, can further increase the risk of device entanglement in the right ventricle.

Anatomy of structures adjacent to the tricuspid valve also has implications for tricuspid intervention. Any devices manipulating the tricuspid annulus near the anteroseptal commissure can run the risk of perforation into the aorta. Additionally, any devices manipulating the septal aspect of the annulus can compress the AV node or His bundle and can lead to complete heart block. Furthermore, manipulation of the inferior annulus in particular can run the risk of injury to the right coronary artery.

Access to the tricuspid valve in some respects is easier than access to the mitral valve, as the vena cavae are large and distensible and transseptal puncture is not required for transcatheter therapies. However, devices designed for trans-septal delivery to the mitral valve may not necessarily reach the tricuspid valve in the appropriate angle. Furthermore, transapical access for the right ventricle may be challenging given the thin right ventricular wall, particularly for patients with a dilated right ventricle from tricuspid regurgitation [20].

Finally, the lack of any continuity between the tricuspid valve and the pulmonic valve decreases the risk of outflow obstruction, which is otherwise an important consideration for mitral valve intervention.

Conclusion

Through careful review of the development of the tricuspid valve, anatomy of its distinct components, and its relationship with adjacent structures, one can understand the complex and unique morphology of the tricuspid valve. This knowledge can serve as a foundation for understanding the clinical, hemodynamic, and multimodality imaging assessment of the tricuspid valve and the current and future management for tricuspid valve disease.

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