Comparative Anatomy of Mitral and Tricuspid Valve: What Can the Interventionalist Learn From the Surgeon

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Transcatheter valve interventions on the mitral and tricuspid valves entail increasing complexity. Part of the knowledge that has been generated during the development of mitral devices can be transferred to the tricuspid valve (TV). However, a deeper understanding of the peculiar anatomy of the TV and of the right heart chambers, together with differences and similarities between the two valves, is fundamental. This report compares the anatomy of the mitral and tricuspid valves, and its inferences with regard to transcatheter treatments.

CONDENSED ABSTRACT
This report explores anatomical similarities and differences between the mitral and the tricuspid valves, and their implications with regard to transcatheter treatments.

Keywords: tricuspid valve, mitral valve, transcatheter therapies, comparative anatomy, multimodality imaging

INTRODUCTION
Transcatheter valve therapies deeply changed the treatment of heart valve disease over the last decade. Shifting from aortic valve interventions (TAVI), more reproducible and with less anatomical variables, toward the AV valves entails increasing complexity and deeper knowledge of these two valves. The development of transcatheter mitral valve (MV) therapies was much more slower, mainly due to the structure and complexity of the MV apparatus and its pathology. With the development of transcatheter tricuspid valve (TV) therapies, interventionists are dealing with an even more stimulating anatomical scenario. Part of the knowledge that has been generated during the development of mitral devices can be transferred to the TV. Therefore, a deep knowledge of the tricuspid anatomy and of the right heart chambers, comparing the differences between the two AV valves, becomes fundamental (1). In this report, the anatomical similarities and differences between mitral and tricuspid apparatus, and their impact (effect) with regard to transcatheter treatments (Table 1) will be addressed.
LEFT ATRIUM, RIGHT ATRIUM, AND INTERVENTIONAL ACCESS

Anatomical Description

Left Atrium

The left atrium (LA) is the cardiac chamber that normally receives pulmonary venous drainage from the four pulmonary veins. Its septal surface is characterized by the flap valve of the fossa ovalis (septum primum), in contrast to the limbus (septus secundum) of the fossa ovalis present on the right atrioseptal surface (Figure 1).

Right Atrium

The right atrium (RA) consists of a curved posterior groove continuous with the superior and inferior venae cavae, a flat interatrial septum, a trabeculated dome, and the TV. In comparison to the LA, the RA has thinner walls and dilates more easily given the same degree of pressure overload.

Interventional Considerations

Different interventional accesses to the LA have been adopted, including direct transatrial, transapical, transarterial retrograde, and transseptal.

Transapical and transarterial retrograde routes are currently used only in really specific situations and have almost been abandoned.

The transseptal access, through the inferior vena cava favored by the crista dividens, is currently the preferred route for most transcatheter MV repair techniques and its usage is quickly increasing for mitral valve-in-valve and valve-in-ring procedures, since it showed superior safety compared to the apical one (2, 3). Transapical access is the most used approach for native MV replacement and for transcatheter neo-chordal implantation, and it will be discussed below in the section describing the ventricles.

Transseptal catheterization is a safe and well-known approach to the LA and, therefore, to the MV. As an example, transseptal route is used for MitraClip (Abbott Vascular, USA) and for direct annuloplasty with the Cardioband device (Edwards Lifesciences, USA). Both of the devices are delivered through a transjugular approach (Trialign, Forma).

Since the TV is approached directly without transseptal puncture, the support provided by the interatrial septum to the catheter in transseptal MV procedures is missing, resulting in a complete lack of stabilization. The absence of the septal support results in diving into the right ventricle (RV) and lack of coaxiality. This represents a major issue, making navigation in the RA more challenging and less controlled.

MITRAL AND TRICUSPID ANNULI

Anatomical Description

The Mitral Annulus

The mitral annulus is reinforced at each extremity of the base of the anterior leaflet, by two dense triangular fibrous structures: the antero-lateral (or left) and the postero-medial (or right) fibrous trigones (Figure 2) (2). Very important, the MV annulus has a 3D saddle-shape configuration and its shape varies through the cardiac cycle (3). Four anatomical structures close to the mitral annulus are at risk of injury during interventional procedures:

(I) The circumflex artery, which runs posteriorly and could be injured, especially during annuloplasty;

(II) The coronary sinus, which skirts the attachment of the posterior leaflet;

(III) The bundle of His which is located near the right trigone (medial commissure);

(IV) The non-coronary and left coronary aortic cusps which are in close relationship with the base of the anterior leaflet, the so-called mitro-aortic fibrous continuity (there is a 6–10 mm safety zone in this area).

The Tricuspid Annulus

The right AV Junction delineates the change between the RA and the TV leaflets (Figure 3). Contrarily to the mitral one, the tricuspid annulus is tiny and difficult to identify and delimitate; annular calcifications are almost absent. In pathologic conditions, such as long lasting tricuspid regurgitation (TR), the TV annulus tends to become planar (4, 5).

Abbreviations: AV, atrio-ventricular; TAVI, transcatheter aortic valve implantation; MV, mitral valve; TV, tricuspid valve; LA, left atrium; RA, right atrium; LAA, left atrial appendage; RAA, right atrial appendage; TEE, transoesophageal echocardiography; TTE, trans-thoracic echocardiography; ICE, intra-cardiac echocardiography; LV, left ventricle; RV, right ventricle; PM, papillary muscle; LVOT, left ventricle outflow tract; RVOT, right ventricle outflow tract.
TABLE 1 | Similarities and anatomical differences between mitral and tricuspid valve apparatus, and their implications with regard to transcatheter treatments.

| Left ATRIUM and LAA | Right ATRIUM and RAA | Interventional considerations |
|---------------------|----------------------|------------------------------|
| • Thicker walls than the RA | • Thinner and more distensible walls | • RA is reached either from SVC or IVC |
| • Smooth atrial cavity | • Presence of Crista Terminalis | • LA is reached mostly through the septum and provides support to device delivery system |
| • Long and narrow trabeculated LAA | • Wide and blunted RAA | • Higher chance of LAA perforation |
| • Presence of PVs orifices | • Presence of SVC, IVC, and CS orifices | |

**Mitral ANNULUS**
- Attached to 2 fibrous trigones (AL-PM)
- Saddle-shaped in systole
- Fibrous structure is thick
- Contiguity with the His bundle (PM commissure), the coronary sinus and the Cx artery (posterolateral region)

**Tricuspid ANNULUS**
- Attached to only 1 trigone (PM)
- Easily distensible with thinner and almost virtual fibrous structures
- Largest orifice of all valves (7–9 cm)
- Contiguity with the Koch triangle, RCA (anteroposterior) and aortic cusps

**Mitral LEAFLETS and COMMISSURES**
- 2 leaflets (A-P) and 2 commissures
- Thicker and more resistant than TL

**Tricuspid LEAFLETS and COMMISSURES**
- 3 leaflets (A-P-S) and 3 commissures
- Thinner, translucent and more fragile

**Mitral CHORDAE TENDINAE**
- Thicker and more resistant.
- Bifurcated/trifurcated at the free edge
- Extend directly from the heads of PMs

**Tricuspid CHORDAE TENDINAE**
- Thinner and more fragile
- Single attachment at the free edge
- Originating from various level of PMs and can attach directly to the RV wall

**Mitral PAPILLARY MUSCLES**
- 2 papillary muscles (AL-PM)
- Single bulky or multiple heads
- No PMs is attached to the septum

**Tricuspid PAPILLARY MUSCLES**
- 3 papillary muscles (ANT dominant- POST-SEPT, multiple and thinner heads)
- Can originate from the septum

**Left VENTRICLE and LVOT**
- Thicker walls than the RV (3:1)
- Absence of Moderator Band
- MV is in continuity with the AV through the mitro-aortic curtain cohoctic cavity

**Right VENTRICLE and RVOT**
- Thinner and more distensible walls (1:3)
- Presence of Moderator Band
- TV and PV are widely separated
- Crescentic cavity

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RA, right atrium; LA, left atrium; RAA, right atrial appendage; LAA, left atrial appendage; PVs, pulmonary veins; MV, mitral valve; TV, tricuspid valve; PV, pulmonary valve; SVC, superior vena cava; IVC, inferior vena cava; CS, coronary sinus; AL, anterolateral; PM, posteromedial; A, anterior; P, posterior; S, septal; AS, anteroseptal; Cx, circumflex artery; RCA, right coronary artery; AR, aortic regurgitation; TEE, transesophageal echo; ICE, intracardiac echocardiography; EROA, effective regurgitant orifice area; PMs, papillary muscles; LVOTO, left ventricular outflow tract obstruction; RVOTO, right ventricular outflow tract obstruction; TMVR, transcatheter mitral valve replacement; RV, right ventricle; AV, aortic valve. This table has been adapted from Taramasso et al. (1).

**FIGURE 1** | Comparison of the atrial septal surfaces. (A) The septal surface of the left atrium is characterized by the flap valve of the fossa ovalis (septum primum), in contrast to the limbus of the fossa ovalis (*) present on the right atrioseptal surface (B). The source of light indicates the fossa ovalis, the blue band depicts the position of the aortic non-coronary sinus. LA, left atrium; MV, mitral valve; SP, septum primum; IVC, inferior vena cava; RA, right atrium; RAA, right atrial appendage.
The more anterior location of the TV compared to the MV (which is much more “TEE-friendly”) makes intraprocedural TEE guidance particularly demanding in tricuspid procedure. In some circumstances, a combination of TEE, TTE and intracardiac echocardiography (ICE) is needed to obtain adequate imaging quality. The major interventional issue related to the TV compared to the MV is its larger orifice (Fig. 5). If in normal conditions the TV area can already reach up to 9 cm², this area will be much larger in the presence of functional TR, representing more than 90% of TR etiology. In such a condition, the regurgitant orifice area is often bigger than 1 cm², i.e., more than double than in mitral position usually central and with a larger coaptation gap compared to MV. Therefore, a complete obliteration of the regurgitant area can be extremely cumbersome with the current repair devices. Similarly, it is easy to understand that also a replacement device has to be extremely big to cover the whole TV area. The large anatomy and the absence of annular calcifications are probably the two most important challenges to obtain sealing with a replacement device in TV position compared to the MV. The proximity of other cardiac structures has interventional implications in both mitral and tricuspid position. A peculiarity of the TV is the contiguity of the AV Node and His bundle (Fig. 4), which is located in proximity of the septal TV annulus, close to the antero-septal commissure (the most common therapeutic target in MitraClip tricuspid procedures). In fact, an acute and complete AV Block (or even asystolia) can be induced just by the contact of any device with the His bundle, due to its compression.

Another important anatomical difference between MV and TV annuli from an interventional perspective is the different risk of coronary injury. The risk of coronary damage during interventional mitral or tricuspid procedures is mainly present in annuloplasty procedure (both direct and indirect), and it is

Three anatomical structures close to the tricuspid annulus could be at risk of injury during interventional procedures:

(I) The non-coronary sinus of Valsalva, in particular the commissure between the non-coronary and the right coronary aortic cusp (especially in annuloplasty procedures);

(II) The bundle of His, which penetrates the central fibrous body and runs underneath the membranous septum 3–5 mm from the antero-septal commissure (the true landmark of His bundle) (Fig. 4);

(III) The right coronary artery, the large single vessel coursing down the right AV groove and surrounding anteriorly the anterior TV leaflet.
highly dependent on the coronary anatomy and dominance of the specific patients (Figure 4). Every therapy addressing the tricuspid annulus in a direct way, especially for unpractised operators, implies an augmented risk of damaging the right coronary artery.

VALVE LEAFLETS

Anatomical Description

The Mitral Leaflets

The MV comprises two leaflets, the anterior (or aortic) and the posterior (or mural), which are separated by two commissures (Figures 2, 5) and without the septal attachment. The valve leaflets are segmented into six sections: from P1 to P3 for the posterior and from A1 to A3 for the anterior. This classification has been useful in describing morphology observed during surgical operation (6), multiplane 2D TEE echocardiography and 3D echocardiography (7).

The Tricuspid Leaflets

The TV comprises three leaflets: the anterior, the posterior and the septal, which are separated by three commissures. The septal leaflet is characteristic of the TV, with either direct chordal attachment to the septum or through the so-called Lancisi conal papillary muscle (PM). The TV leaflets are thinner, more translucent and more fragile compared to the MV (Figures 3, 6).

Interventional Perspectives

Due to the different tissue property and characteristics, the chance of damaging or tearing the TV leaflets is higher compared to the MV. This has to be taken into consideration in case of leaflet repair, as MitraClip in tricuspid position.

SUBVALVULAR APPARATUS

The subvalvular apparatus of the MV and TV is similar and consists of two different structures with different characteristics: the papillary muscles (contractile function) and the chordae tendineae (elastic function).

Papillary Muscles

Mitrval

The mitral PMs, which insert on the left ventricular (LV) free wall, are usually organized into two groups, which are the posteromedial and the anterolateral, situated just below the corresponding commissures (Figure 7). Not rarely, a third intermediate PM is found implanted between them, providing the chordae to A2 or P2 segments. Apical displacement of the posteromedial PM secondary to lateral myocardial infarction is the most frequent mechanism to underline asymmetrical tethering and functional MR post-infarction chronic ischemic heart disease.

Tricuspid

The tricuspid PMs are inserted on the right ventricular (RV) wall and usually organized into three groups: anterior, posterior and septal (Figures 7, 8). The anterior PM is the dominant and is implanted on the anterior wall of the RV, near the...
FIGURE 6 | Multimodality imaging of the TV. (A) Deep transgastric 2D TEE view, displaying the TV in short axis from the ventricular side. (B) Same en face view derived from MSCT angiography. (C) Short-axis atrial view of the TV on 3D TEE and during surgery. (D). Red asterisks are the commissures. AL, anterior leaflet; LV, left ventricle; PL, posterior leaflet; RV, right ventricle; SL, septal leaflet. This image has been adapted from Taramasso et al. (1).

FIGURE 7 | Comparison of mitral and tricuspid PMs. (A,B) Each group of papillary muscles comprises either a single bulky papillary with multiple heads or otherwise several thinner papillary muscles from which arise the numerous chordae attaching to the leaflets. They are implanted on the muscular wall of the left ventricle at a junction situated ∼1/3 from the apex and 2/3 from the annulus. The position is varying little; the anterolateral PM is implanted at the junction between the septum and the posterior wall of the ventricle. The posteromedial PM is inserted on the lateral wall of the ventricle. The length of the PMs is variable, ranging from 2 to 5 cm. Importantly, no PMs attach to the left side of the ventricular septum.

apex, fusing with the moderator band. The chordae tendineae extend from the free margin to the PM. Three types can be described: the basal chordae (tertiary), the intermediary chordae (secondary) and the marginal chordae (primary), which are the most represented (8). Basically, having the TV three leaflets, with the posterior often divided in further scallops, it presents a more complex chordal structure in comparison to MV (9).
**Interventional Perspectives**

The main interventional issue related to the subvalvular apparatus is the risk of impingement of any device in the chordal apparatus, once the valve is crossed. Similarly in both MV and TV, the risk is higher in the commissural region, in which the density of chordae is the maximum, while the middle of the valve is chordae-free zone. This is particularly true for leaflet repair devices delivered antegrade, typically with the MitraClip.

**FIGURE 8** | The TV has a more complex chordal structure in comparison to MV. The chordae can be attached directly to the RV wall and septum, differently from the LV. On average, a number of 25 chordae inserts into the TV. The chordal system is hierarchical similar to the left one, dividing the types of chordae in basal, intermediary or secondary chordae and the marginal chordae, attaching to the free edges. The attachment of the marginal or primary chordae is usually single on the right, without bifurcating or trifurcating close to the edge and originating from various levels of the papillary muscles. Even if thinner, the chordae of the TV commissures are trifurcated with a characteristic fan-like disposition. CT, Chordae tendineae; PM, papillary muscle; MV, mitral valve; TV, tricuspid valve. LMCA, left main coronary artery (light blue circle). Courtesy of Dr. M. Reisman, University of Washington.

**FIGURE 9** | The septal surface of the LV may be considered to have a sinus portion, most of which is trabeculated, and a smooth outlet (LVOT) portion (A). The part of the sinus portion of the septum immediately beneath the mitral valve may be termed the inlet septum, and the rest of the sinus portion, the trabecular septum. The LVOT lies in front and to the right of the anterior mitral leaflet, corresponding to the inlet portion on the right ventricular side of the septum, and includes the atrioventricular septum. On the right side, the septal leaflet is the only one attached to the septum, but it leaves the RVOT free (B). The lowermost of the small septal muscles attaches posterior to the trabecula septomarginalis and the uppermost, called the medial or conal PM (muscle of Lancisi), to the posterior limb of the septal band. The septal PM is almost not affected by tethering in case of RV dilatation. LVOT, left ventricular outflow tract; AV, aortic valve; AML, anterior mitral leaflet; MPMs, mitral papillary muscles; RVOT, right ventricular outflow tract; TPMs, tricuspid papillary muscles. This image has been adapted from Taramasso et al. (1).
In presence of a commissural lesion, the risk of clip impingement is particularly high and can lead to impossibility to retrieve the device or chordal rupture with consequent worsening of the regurgitation. In TV the commissures are almost invariably the antero-septal: a first clip is implanted close to the commissure, where the coaptation defect is minimum, in order to approximate the leaflets, and may facilitate the implantation of further clips on the coaptation line. Since the only location that allows leaflet grasping is at the real commissure, risk of impingement or chordal injury is present in tricuspid clipping procedures. Similarly to the leaflet, also the chordal tissue of the TV is thinner and more fragile compared to MV, and this may increase the risk of damage, especially in case of multiple grasping attempts or in case of chordal impingement.

LEFT VENTRICLE, RIGHT VENTRICLE AND OUTFLOW TRACTS

Anatomical Description

Left Ventricle

The LV consists of a larger sinus portion, which supports the MV and includes the apex, and a much smaller outlet (outflow) portion beneath the aortic semilunar valve. Contrary to the RV, the inlet and outlet valves of the LV lie juxtaposed within its base, and inflow and outflow portions are separated by a curtain represented by the anterior MV leaflet (Figure 9). The LV trabeculations are characteristically fine compared with those in the RV (10).

Right Ventricle

The RV has a large sinus portion that surrounds and supports the TV (inlet portion) and includes the apex and an infundibulum (outlet portion) that supports the pulmonic valve. The inlet and outlet valves of the RV, opposite to the aortic and MV, are thus widely separated by the “Crista ventricularis” (11), minimizing any risk of right ventricular outflow tract obstruction (RVOT). The entire sinus portion of the RV and most of the infundibulum (both free wall and septum) are coarsely trabeculated (12). The conduction system (bundle of His) perforates the infundibulum and the wide-open angle between them make the risk of RVOT obstruction really low with any type of tricuspid device, in any anatomical context (Figures 9, 10). While transapical LV access is frequently used for aortic and MV procedures, apical RV access presents several issues. The thin and trabeculated RV wall makes this approach potentially risky, especially in the context of RV dilatation and dysfunction associated to functional TR.

CONCLUSIONS

With the fast development of transcatheter TV therapies, physicians are facing up with a new challenging anatomical scenario. A deep understanding of the anatomy of the TV and of the right heart chambers, and their differences compared to the left-heart, is fundamental to improve safety and efficacy. The specific anatomical features of the TV, the low quality of intraprocedural TEE guidance and the absence of a standardized nomenclature remain major open issues to be addressed in TV intervention.

AUTHOR CONTRIBUTIONS

AP and MT wrote the manuscript. MZ, MR, and FM supervised, contributed with specific iconography and revised critically the paper.
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