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Right Atrioventricular Valve Leaflet Morphology Redefined

Implications for Transcatheter Repair Procedures

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ABSTRACT

OBJECTIVES The authors aimed to comprehensively detail the right atrioventricular valve functional leaflet anatomies.

BACKGROUND The rapid development of both surgical and percutaneous repair techniques for tricuspid regurgitation has renewed interest in variations in the morphology of the right atrioventricular valve.

METHODS The functioning right atrioventricular valves of 40 reanimated human hearts were imaged using Visible Heart methodologies. Hearts were then perfusion-fixed and dissected, uniquely allowing for the comparative assessments of functional versus fixed valve anatomies from the same set of donor hearts.

RESULTS The right atrioventricular valves have "3-leaflet" configurations in 57.5% and "4-leaflet" configurations in the remaining hearts. For 4-leaflet valves, extra leaflets were commonly observed in the most inferior regions of the annuli. No difference in valve perimeters between 2 valve types were observed (112.2 vs. 117.1 mm; $p = 0.14$). In 3-leaflet valves, septal, mural, and superior leaflets occupied 32.2 ± 6.5%, 15.9 ± 5.5%, and 25.5 ± 6.2% of the annulus, respectively, whereas in the 4-leaflet arrangements, these values were 27.0 ± 5.8% (septal), 12.0 ± 4.5% (inferior), 13.7 ± 9.4% (mural), and 19.8 ± 6.1% (superior). The muroseptal/inferoseptal commissures were usually located in the cavotricuspid regions, whereas the inferomural and superomural commissures were in the right atrial appendage vestibule area.

CONCLUSIONS The right atrioventricular valve has 4 functional leaflets in more than 40% of cases. The authors found that the inferomural region is the most variable area of the valve and believe that anatomic variation is an important consideration for planned interventions. (J Am Coll Cardiol Intv 2019;12:169-78) © 2019 by the American College of Cardiology Foundation.

The right atrioventricular valve, located between the right atrium and right ventricle, is one of the most complex and variable structures within the human body. It has been conventional wisdom that this valve, commonly referred to as the tricuspid valve, has 3 leaflets: anterior, septal, and posterior (1-3). However, several more recent anatomic studies have highlighted that the tricuspid valve is more heterogeneous than previously thought and frequently presents as either bicuspid or quadricuspid in nature (4,5). Consequently, it can be hypothesized that a detailed configuration of the valve's structure is still unresolved, with large discrepancies between reported investigations stemming from the ambiguous criteria for the differentiation of the individual components of the valve apparatus.

Until recently, the valve of the right atrioventricular junction was rarely the center of much clinical attention. However, rapid developments of both surgical and percutaneous tricuspid regurgitation repair techniques have renewed this interest (6). Nevertheless, extensive anatomopathological

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ABBREVIATIONS AND ACRONYMS

PM = papillary muscle

SB = septal band

description of the right atrioventricular valve exists, functional anatomy of this valve is still poorly understood. Moreover, imperfect nomenclature is used that needs refinement. Thus, the aim of our study was to detail right atrioventricular valve anatomies of human hearts using both unique visualizations of reanimated hearts as well as traditional dissections of these same specimens afterward.

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METHODS

The study protocol for this research conformed to the ethical guidelines of the 1975 Declaration of Helsinki and was reviewed and approved by the institution review board at the University of Minnesota. Fresh human heart specimens, deemed nonviable for transplantation, were procured from organ donors as gifts for research by LifeSource (Minneapolis, Minnesota) with informed consent from the donor's closest relatives for the use of the hearts for our laboratory's research purposes.

STUDY POPULATION. A total of 40 human hearts (60% females) were investigated in this study. Mean donor age and body mass index were 57.1 ± 15.6 years and 28.5 ± 6.4 kg/m^2, respectively. The cardiac-related clinical histories were known in 29 cases and included: arterial hypertension (n = 19); coronary artery disease (n = 9); myocardial infarction (n = 2); atrial fibrillation (n = 8); left ventricular hypertrophy (n = 6); mitral regurgitation (n = 2); rheumatic fever (n = 2); and aortic stenosis (n = 1).

FUNCTIONAL ENDOSCOPIC VIDEO RECORDING AND TISSUE PRESERVATION. All human hearts in this study were reanimated using Visible Heart methodologies as previously described (7–9). Briefly, donated hearts deemed not viable for transplantation in a human recipient were arrested using a high potassium cardioplegic solution and explanted using standard cardiac transplant procedures. The great vessels were cannulated to allow for attachment to the Visible Heart apparatus. Once attached, the heart was reperfused with a warm Krebs-Henseleit buffer to return the specimen to normal body temperature (37°C). Hearts were then defibrillated, and all 40 specimens displayed typical, noninnervated sinus rhythms.

Both 6- and 4-mm endoscopic cameras (Olympus Optical, Tokyo, Japan) were used for real-time imaging of the functioning cardiac anatomies. The utilization of a clear buffer solution enabled high-resolution, intracardiac endoscopic imaging of the functioning hearts (9). For a given specimen, endoscopic videos were recorded from within the right atrium to visualize the motion of the tricuspid valve throughout the cardiac cycle.

Next, each reanimated heart was perfusion fixed under pressurization (40 to 50 mm Hg) with a 4% paraformaldehyde pH-buffered solution delivered through the great vessels for at least 24 h to preserve an approximation of the end-diastolic state (10). To gain access to the right atrioventricular valves for these static analyses, the right atrium of each specimen was opened using an intercaval incision extending from the orifice of the superior vena cava to the orifice of the inferior vena cava.

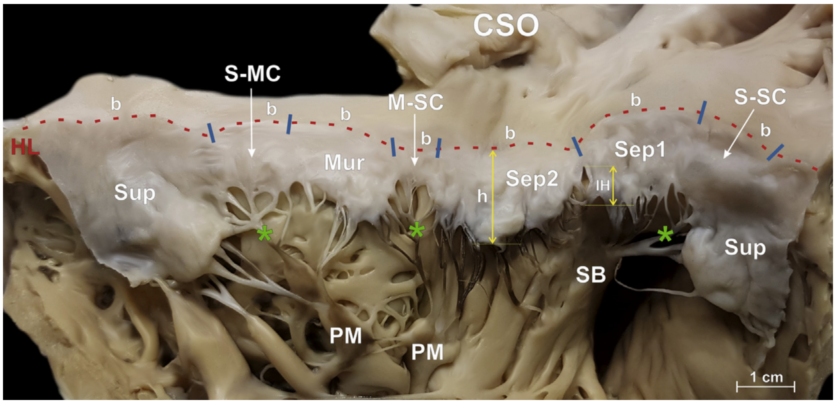
LEAFLETS, COMMISSURES, AND SCALLOP IDENTIFICATION. We applied precise morphological criteria to define the individual parts of the right atrioventricular valve complex similar to those used for previous mitral valve anatomic studies (11–13). The proper, attitudinally correct human anatomy nomenclature was employed to name all components of the right atrioventricular valve (14,15). First, all commissures and leaflets were identified and counted. Commissures were defined as an area within the valve complex, located between 2 adjacent leaflets. Commissures are characterized by an arched appearance and are accompanied by a commissural tendinous cord (a fan-shaped cord) that originates from the respective papillary muscle (or septal band) located directly beneath the commissure. Additionally, commissures were considered to have different geometries (area between leaflets) compared with indentations (point between scallops).

A leaflet was defined as a fold of tissue that was located between 2 commissures. These were independent functional components of a given valve that reached the geometrical center of the valve, coapted along the zones of apposition, and touched at least 2 other leaflets during systole. Leaflets were also typically divided into scallops by indentations.

We further distinguished between the anatomic scallops and functional scallops. An anatomic scallop was defined as an individual part of the leaflet that was separated by an indentation. A functional scallop was identified when no indentation was present in the fixed specimen, but when the independent scallop was clearly visible within the associated functional video and with leaflet plication (or wrinkle) occurring in the locations of the possible indentation.

STATIC MEASUREMENTS. All linear measurements of the fixed specimens were obtained using 0.03-mm precision electronic calipers (LIMIT, Stockholm, Sweden). Boundaries for identifying parts of a given

FIGURE 1 Cadaveric Heart Specimen



A right atrioventricular valve in 3-leaflet configuration is shown. The annulus was opened by an incision through the middle of the superior (Sup) leaflet. All leaflets and commissures were marked. The **asterisks** indicate the commissural cord. b = base length; CSO = coronary sinus ostium; h = scallop height; HL = hinge line; IH = indentation height; I-MC = inferomural commissure; I-SC = inferoseptal commissure; Mur = mural leaflet; PM = papillary muscle; SB = septal band; Sep1, Sep2 = septal leaflet scallops; S-SC = superoseptal commissure.

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right atrioventricular valve were marked by pins. Measured values for the following dimensions were obtained (Figure 1):

1. The valve base (or circumferential) length—measured alongside the attachment line (hinge) to the annulus, for all leaflets, scallops, and commissures.
2. The valve height—determined as the maximum distance from the annulus attachment point (hinge) to the free edge, measured for leaflets and scallops in the central part of their base.
3. The indentation height—measured from the free edge of the smaller scallop to the furthest point of indentation in the leaflet.

The annulus perimeter was defined as the sum of the base lengths for all identified leaflets and commissures.

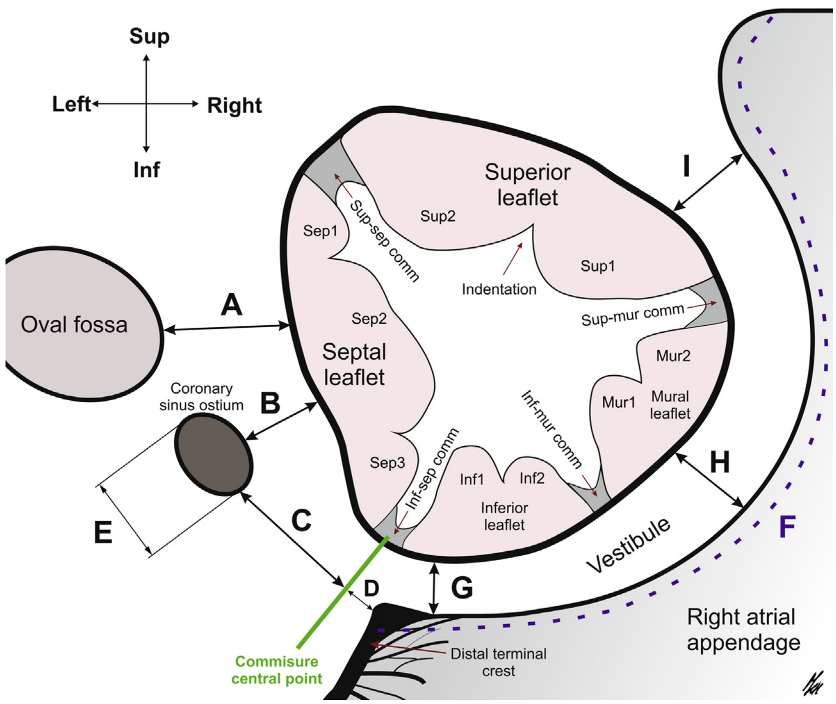
Additionally, relative anatomic relationships between the right atrioventricular valve and the surrounding right atrial structures were specified (Figure 2). These included the shortest distances from the annulus to the anteroinferior rim of the oval fossa (A) and to the lower margin of the coronary sinus ostium (B). The relative positions of the muroseptal/inferoseptal commissures were determined in relation to the coronary sinus ostium (distance from the ostial right margin to the central point of the commissure) (C) and to the main bands of the distal terminal crest (distance from terminal crest to the central point of the commissure) (D). The transverse diameters of the coronary sinus ostium (E) and the right atrial appendage ostium diameters, measured alongside the annulus (F), were also assessed. Finally, the width of the smooth-walled vestibule between the right atrial appendage and right atrioventricular orifice, was measured at 3 levels: the end of the terminal crest (G), the midpoint (H), and the superior border (I) of the right atrial appendage.

STATISTICAL ANALYSES. Data were presented as mean values with the corresponding SDs and ranges, median values with corresponding lower and upper quartiles, and/or determined percentages. Shapiro-Wilk tests were used to determine whether the quantitative data were normally distributed. To verify a relative homogeneity of variance, we performed Levene's tests. We also used the Student's *t*-test and the Mann-Whitney *U* tests for statistical comparisons. Qualitative variables were compared using the Fisher exact tests of proportions for categorical variables. We performed these statistical analyses using StatSoft STATISTICA 13.1 software for Windows (StatSoft, Tulsa, Oklahoma). An obtained p value of 0.05 was considered to be statistically significant.

RESULTS

The right atrioventricular valve elicited 3 defined leaflets (Figure 3, Online Video 1) in 57.5% of the cases, and a fourth leaflet (Figure 4, Online Video 2) was considered as present in the remaining 42.5% of hearts.

FIGURE 2 Schematic View of the Right Atrioventricular Valve in 4-Leaflet Configuration and Surrounding Right Atrial Structures in Diastole



Valve commissures (comm) and leaflets divided into scallops were marked, tendinous cords and papillary muscles were not shown. For measurement descriptions **(A to I)**, please see the Methods section. Inf = inferior; Inf 1, Inf 2 = inferior leaflet scallops; Mur = mural, Mur 1, Mur 2 = mural leaflet scallops; Sep = septal; Sup = superior; Sup 1, Sup 2 = superior leaflet scallops; other abbreviations as in Figure 1.

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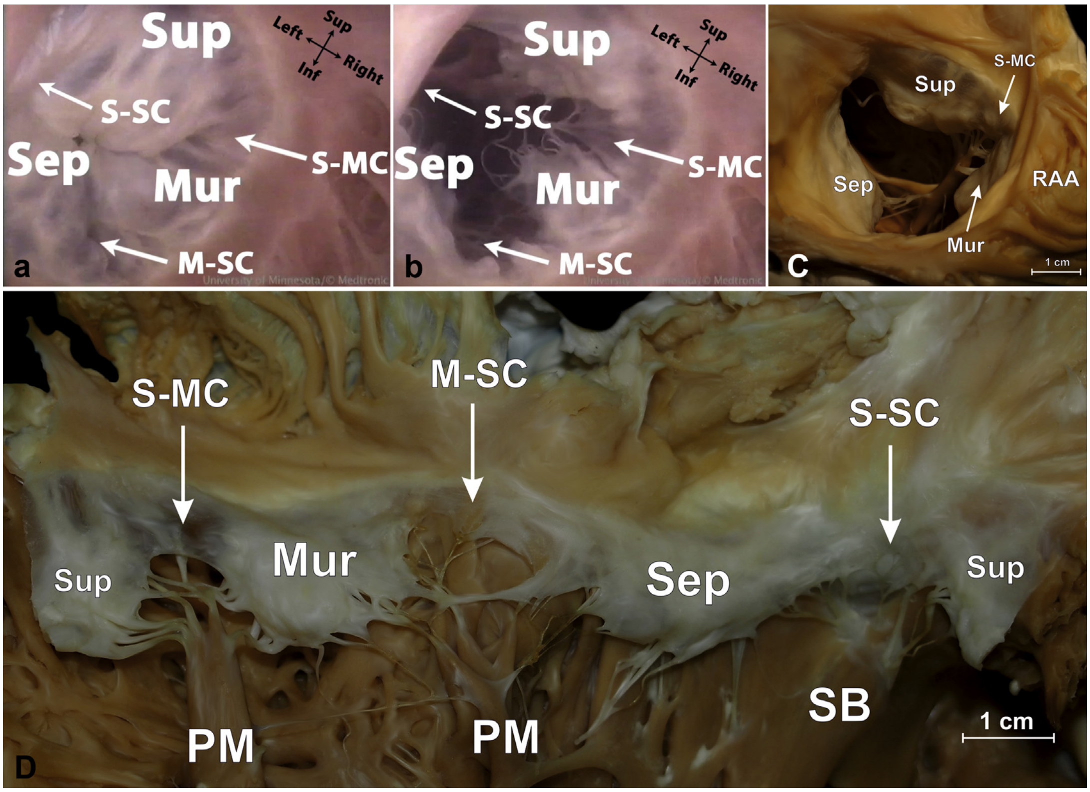
For the 3-leaflet anatomies (tricuspid valve), we named the leaflets as follows: septal, mural (or posterior), and superior (or anterior). These leaflets were connected by muroseptal, superomural, and superoseptal commissures, respectively. In 34.8% of the 3-leaflet valves ($n = 8$), a fold of tissue (both anatomic and functional) was observed to be present within the doubled muroseptal commissure, which did not meet the defined criteria of a true leaflet.

For the 4-leaflet configurations (quadricuspid valve), an extra inferior leaflet was observed to be present between the septal and mural leaflets: that is, in the most inferior regions of the annulus. When such an extra leaflet was present, they were connected by inferoseptal, inferomural, superomural, and superoseptal commissures. In 17.7% of the 4-leaflet valves ($n = 3$), doubled inferoseptal commissures with a fold of tissue were observed.

Table 1 details the donors' demographics and the leaflet and commissure dimensions for all 40 specimens studied. Regardless of either a 3- or 4-leaflet valve configuration, cumulatively, their commissures occupied a similar portion of the annulus (26.4 ± 4.5% and 27.6 ± 4.5%; $p > 0.05$). The same was observed for leaflets (73.6 ± 4.5% and 72.4 ± 4.5%; $p > 0.05$). In the 3-leaflet right atrioventricular valves, septal, mural, and superior leaflets occupied 32.2 ± 6.5%, 15.9 ± 5.5%, and 25.5 ± 6.2% of the annulus, respectively. In 4-leaflet presentations, septal leaflets occupied 27.0 ± 5.8% of the annulus; inferior leaflets 12.0 ± 4.5%; mural leaflets 13.7 ± 9.4%, and superior leaflets 19.8 ± 6.1%. A significant reduction of septal ($p = 0.01$) and superior ($p = 0.01$) percentages of leaflet extensions were observed in 4-leaflet valves relative to 3-leaflet valves, that is, with no differences in measured perimeter absolute values ($p > 0.05$).

Scallops were numbered in a counterclockwise manner (Figure 2). Anatomically, septal leaflets were not subdivided by scallops in 30% of the hearts but print & web 4C/FPO

FIGURE 3 **Right Atrioventricular Valve in 3-Leaflet Configuration**

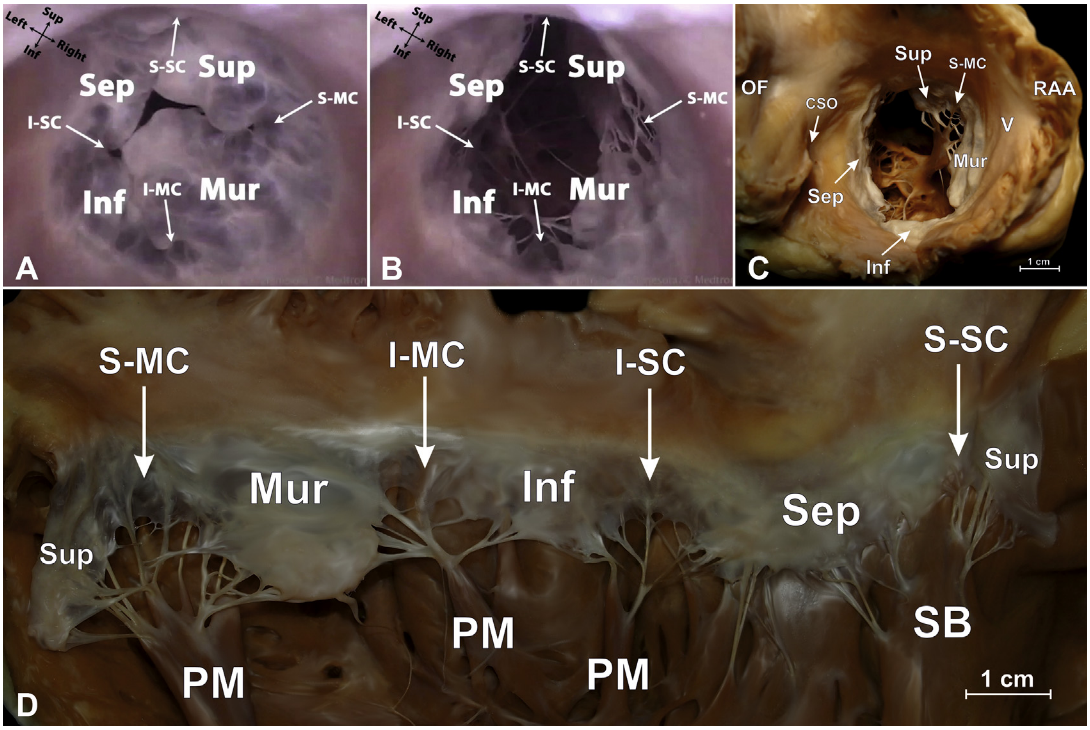


Functional endoscopic view of the valve in **(A)** systole and **(B)** diastole. Dissection images of the formalin fixed valve as viewed **(C)** from the right atrium and **(D)** with the annulus opened by an incision through the middle of the superior (Sup) leaflet. For more functional images, please see Online Video 1. M-SC = muroseptal commissure; RAA = right atrial appendage; Sep = septal leaflet; S-MC = superomural commissure; other abbreviations as in **Figures 1 and 2**.

were subdivided into 2 in 50.0%, 3 in 17.5%, and 4 in 2.5% of the cases. Mean indentation heights between septal scallops in the 2-scallop configurations was 5.3 ± 2.5 mm and accounted for 39.7% (range 15.7% to 81.2%) of the smaller scallop heights. In the 3-scallop subdivided septal leaflets, indentations between septal 1 and septal 2, as well as septal 2 and septal 3, scallops were similar in size (4.8 ± 2.8 mm, 37.8% and 4.9 ± 1.3 mm, 42.4%, respectively). Mural leaflets were usually not subdivided (70.0%) and less often had 2 (22.5%) or 3 (7.5%) scallops. Mean mural indentation height for the 2-scallop anatomies was 5.9 ± 2.3 mm (44.2%; range 33.1% to 63.6%). The superior leaflets were not subdivided by scallops in 65% of cases. Two scallops were found in 30.0% of superior leaflets (mean absolute indentation height 5.9 ± 2.0 mm and mean relative indentation height 37.8%; range 18.4% to 74.5%) and 3 scallops were present in 5.0% of the hearts. The inferior leaflets were not subdivided in 70.6% and subdivided into 2 scallops in 29.4% of the 4-leaflet valves, with mean indentation heights of 3.2 ± 0.9 mm (31.4%; range 22.8% to 44.3%). Functional scallops were found in 4 septal (10.0%), 1 inferior (2.5%), 4 mural (10.0%), and 2 superior (5.0%) leaflets (**Figure 5**, Online Video 3).

In the 3-leaflet right atrioventricular valves, the muroseptal commissure was observed to be located between the coronary sinus ostium and terminal crest in 69.6% of these specimens. In the remaining 30.4%, the commissures were shifted superiorly, beyond the terminal crest. The inferoseptal commissures were commonly located between the coronary sinus ostium and terminal crest in 94.1% of 4-leaflet valves, closer to the coronary sinus ostium than the terminal

FIGURE 4 Right Atrioventricular Valve in 4-Leaflet Configuration



Functional endoscopic view of the valve in **(A)** systole and **(B)** diastole. Dissection images of the formalin fixed valve as viewed **(C)** from the right atrium and **(D)** with the annulus opened by an incision through the middle of the superior (Sup) leaflet. For more functional images, please see Online Video 2. Inf = inferior leaflet; OF = oval fossa; V = vestibule; other abbreviations as in **Figures 1 and 3**.

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crest. Statistically significant differences were found for the measured distances between the coronary sinus ostium and muroseptal or inferoseptal commissures (12.2 vs. 6.5 mm; $p = 0.02$). The width of the right atrial appendage vestibule was measured to be the narrowest at the terminal crest end, and gradually expanded toward the mid-point and superior end (12.1 ± 2.1 mm vs. 13.7 ± 2.9 mm vs. 18.3 ± 4.4 mm; $p < 0.01$).

DISCUSSION

The right atrioventricular valve in the human heart, commonly referred to as the "tricuspid valve," is often a more complex and heterogeneous structure than the left atrioventricular or "mitral" valve, which almost always has only 2 leaflets (12). This high variability leads one to confidently state that no 2 right atrioventricular valves elicit identical configurations. As our study shows, the right atrioventricular valve can be considered as truly tricuspid in only 37.5% of the studied cases, whereas in the remaining hearts we studied here, additional leaflets or doubled commissures with functional folds of tissue were observed. This finding was consistent with previous reports in which a fourth right atrioventricular valve leaflet was identified in 10% to 42% of studied human hearts (4,5). To conclude, the presence of the fourth leaflet or doubled commissures with functional folds should be considered a very frequent anatomic variant of the "tricuspid" valve. The name "tricuspid" might be considered as partially inaccurate for this right heart structure: hence, we propose using the simpler anatomic terminology of the "right atrioventricular valve."

The conventional nomenclature used today defines the "classical" right-atrioventricular valve leaflets as anterior, septal, and posterior. Yet, these anatomic names were derived from extracorporeal views of the human heart viewed orthogonally to the tricuspid annulus. A more accepted general rule in anatomy is to describe any given organ system and/or tissue structure as it would correlate to the human anatomic position. This "attitudinally" correct and anatomically appropriate rule has recently been promoted for the definition of all human cardiac structures (9,14,15). Previous authors have also emphasized the use of an anatomically correct naming system for the right atrioventricular valve subcomponents, including the leaflets (16,17). Here, we employed a modified nomenclature to label the right atrioventricular valve leaflets in our study specimens. The so-called anterior leaflet was determined to be located in the superior part of the annulus and should be noted as the "superior" leaflet. The supposed posterior leaflet is actually located on the right ventricular free wall, and the adjective "mural" is therefore a more appropriate term for this leaflet. The septal leaflet, however, is located on the interventricular septum, thereby justifying its name. In a 4-leaflet valve configuration, the additional leaflet was located between the existing septal and mural leaflets and thus should be termed "inferior" due to its most inferior position within this valve annulus.

As we have shown in this study, the inferior part of the right atrioventricular valve was the most variable anatomic area, presenting with either an additional fourth leaflet or doubled commissure containing a small functional fold of tissue. Such a high degree of variability within valve configurations may result from its embryological origin, specifically, the relatively free movement of the valvular leaflet structures during development. These leaflets emerge through a delamination process from the underlying myocardium usually occurring between the eighth and sixteenth weeks of human development (18). Furthermore, the structures of the right atrioventricular orifice were observed as nonplanar and irregular with slightly triangular annular structures, especially in the inferior/mural region. This in turn, might determine the need for additional leaflets in the inferior regions of the annulus to fully seal the right atrioventricular orifice (19).

In addition to the configuration of the leaflets, the commissures also contribute to effective valve function. It is a common mistake to consider the commissures as various points that can be marked on valve annulus (20). In actuality, commissures typically account for approximately 25% of the annular length of the right atrioventricular valve. In this study, they were readily visible during diastole and folded during systole to serve as ends of the zone of

TABLE 1 Basic Morphometric Features of Leaflets, Commissures, and Surrounding Structures in 3- and 4-Leaflet Right Atrioventricular Valves

	3-Leaflet Valve (n = 23)	4-Leaflet Valve (n = 17)
Female	69.6	47.1
Age, yrs	57.0 (50.5 to 66.5)	62.0 (56.0 to 66.0)
Donors BMI, kg/m^2	27.0 (23.3 to 33.5)	27.6 (24.6 to 31.5)
Post-fixation heart weight, g	504.0 (404.6 to 570.7)	593.8 (468.4 to 700.0)
Valve perimeter, mm	112.2 (96.5 to 121.5)	117.1 (106.6 to 123.9)
Septal leaflet		
Base length, mm	32.5 (28.5 to 42.8)	32.5 (26.3 to 33.6)
Height, mm	18.4 (16.1 to 21.4)	19.7 (16.5 to 21.1)
Scallops		
Not divided	6 (26.1)	6 (35.3)
2	9 (39.1)	11 (64.7)
3	7 (30.4)	–
4	1 (4.3)	–
Mural leaflet		
Base length, mm	14.9 (13.2 to 24.7)	14.9 (11.6 to 20.3)
Height, mm	19.8 (17.1 to 21.7)	20.5 (16.9 to 23.3)
Scallops		
Not divided	14 (60.9)	14 (82.4)
2	6 (26.1)	3 (16.4)
3	3 (13.0)	–
Superior leaflet		
Base length, mm	27.1 (23.3 to 31.3)	21.6 (19.0 to 26.0)
Height, mm	21.5 (18.7 to 27.3)	21.3 (19.1 to 23.4)
Scallops		
Not divided	14 (60.9)	12 (70.6)
2	7 (30.4)	5 (29.4)
3	2 (8.7)	–
Inferior leaflet		
Base length, mm	–	11.9 (10.1 to 20.4)
Height, mm	–	15.6 (12.1 to 18.4)
Scallops		
Not divided	–	12 (70.6)
2	–	5 (29.4)
Muroseptal/inferoseptal commissure base length, mm		
For single commissure	10.1 (7.5 to 11.4)	7.1 (6.3 to 9.3)
For doubled commissure with fold	12.8 (9.1 to 20.2)	12.9 (11.7 to 20.8)
Superomural commissure base length, mm	8.8 (6.8 to 10.4)	7.8 (6.9 to 10.1)
Superoseptal commissure base length, mm	8.5 (7.3 to 9.5)	7.0 (6.1 to 8.4)
Inferomural commissure base length, mm	–	7.5 (5.6 to 8.2)
A – annulus to oval fossa distance, mm	21.9 (19.3 to 22.7)	22.1 (19.2 to 25.1)
B – annulus to coronary sinus ostium distance, mm	11.6 (9.0 to 14.0)	10.9 (9.6 to 17.5)
C – muroseptal/inferoseptal commissure to coronary sinus ostium distance, mm	12.2 (7.7 to 24.7)	6.5 (2.4 to 13.7)
D – muroseptal/inferoseptal commissure to distal terminal crest distance, mm	6.6 (−2.3 to 12.6) 30.4% with negative values*	8.1 (3.1 to 11.9) 5.9% with negative values*
E – coronary sinus ostium transverse diameter, mm	12.3 (10.5 to 12.9)	11.1 (10.0 to 13.1)
F – right atrial appendage ostium diameter, mm	68.6 (57.2 to 77.2)	72.2 (64.5 to 81.0)
G – vestibule terminal crest end width, mm	12.6 (10.7 to 14,1)	11.5 (10.9 to 13.6)
H – vestibule midpoint width, mm	13.3 (12.1 to 14.7)	15.4 (12.2 to 16.8)
I – vestibule superior end width, mm	18.5 (14.3 to 20.1)	17.4 (15.8 to 23.8)

Values are %, median (interquartile range), or n (%). *Negative values represent cases when the commissure is shifted to the superior direction, beyond the terminal crest.
BMI = body mass index.

FIGURE 5 Right Atrioventricular Valve in 3-Leaflet Configuration

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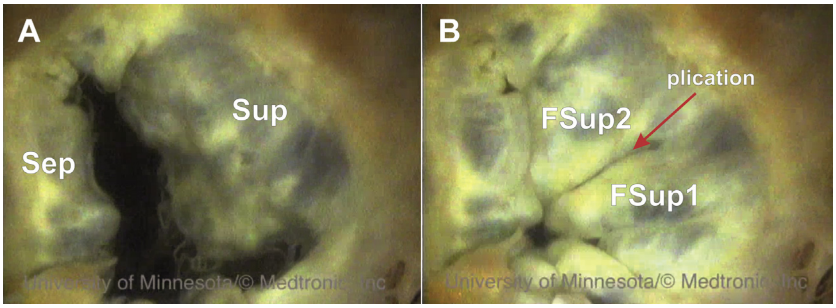

Functional endoscopic view of the valve in **(A)** diastole and **(B)** systole. The superior leaflet (Sup) is not anatomically divided into scallops, whereas functional scallops (FSup1 and FSup2) could be seen when the valve was closed during systole. For more functional images, please see Online Video 3. Sep = septal leaflet.

apposition between leaflets. This folded configuration has even prompted some anatomists to describe "commissural leaflets" (21). Importantly, the appearance of a fourth leaflet and commissure in some of the specimens studied here was accompanied by a fourth papillary muscle complex clearly identified from the functional Visible Heart footage. The fourth commissure creates an additional zone of apposition and significantly modifies geometry and functional properties of the right atrioventricular valve. This 4-leaflet and 4-commissure configuration may significantly reduce the efficacy of transcatheter procedures designed for a "tricuspid" valve configuration.

A wide range of percutaneous annuloplasty devices designed for functional right atrioventricular valve repair are currently being tested or are already in clinical use (6). Multiple concepts have been generated with the primary goal of these devices to induce the plication of adjacent leaflets, thereby reducing the functional size of the right atrioventricular orifice (22). The intended plication can be achieved by placing pledgeted sutures along the right ventricle free wall starting from the muroseptal/inferoseptal commissure and moving to the superomural, exactly in the highest area of anatomic variability. Despite this structural inconsistency, the region should still be recognized as the safest zone for plication placement (6). However, the presence of a fourth leaflet, fourth commissure, and additional papillary muscle complex might justify the consideration of an alternative treatment plan.

The septal region of the right atrioventricular valve demands specific attention when considering a plication procedure due to the proximity of the atrioventricular node, His bundle, and coronary sinuous ostium. Further, the cavotricuspid isthmus region, located to the right of the coronary sinus ostium, is often tenuous and should also be avoided during such interventions if possible (23). Conversely, the vestibule, located between right atrial appendage ostium and the valve annulus, is relatively wide (more than 10 mm) and is considered to be one of the safest zones for plication placements. The vestibule contains a thin muscular layer, and extensive fat deposits make it an ideal region for anchoring devices. However, attention must still be paid to the right coronary artery that traverses alongside the annulus and courses within 3 mm of the vestibule at its most inferior aspect (24). Consequently, it can be argued that the right coronary artery could be directly injured or occluded as a result of anatomic modifications arising from the plication of this region of the annulus (25). The terminal crest is defined as the border between the cavotricuspid isthmus and vestibule area (23,24). Unfortunately, the central point of the muroseptal commissure (for 3-leaflet valves) frequently overlaps (in 70% of cases) this vulnerable cavotricuspid region, whereas the inferoseptal commissure (for 4-leaflet valves) is located in this area in 94% of human hearts. Finally, the inferomural and superomural commissures were found to be located within the right atrial appendage vestibule area for every heart specimen we examined.

The concept of scallops has remained a topic of relatively minor attention for most clinicians. However, the scallops can play significant valvular roles and thus should not be dismissed. Anatomic scallops can be defined as a subcomponent of the leaflets, which are differentiated from a leaflet with indentations (not clefts) (12). Interestingly, some of the specimens studied here displayed functional scallops that were highlighted by the Visible Heart footage (**Figure 5**, Online Video 3) but could not be anatomically differentiated due to the lack of an indentation. The primary role of both the defined anatomic and functional scallops seems to be to adjust the leaflet during systole by providing the ability for plication (**Figure 5**). Perhaps, then, the presence of the scallops should be a major consideration during transcatheter repair procedures such as MitraClip (Abbott Vascular, Santa Clara, California) implantation to treat severe right atrioventricular valve regurgitation (26). The incorrect assessment of the valve geometry could lead to poor placement of the implanted device (involving only small or long scallops, for example) and potentially result in a minimal reduction in regurgitant volume and therefore worse patient outcomes. Unfortunately, the presence of these anatomic and functional scallops cannot be easily predicted, thus detailed pre-procedural imaging of the valve is required to ensure good patient outcomes in these cases (27).

STUDY LIMITATIONS. Our present study was a unique opportunity to investigate the morphologies of the right atrioventricular valve using both real-time functional imaging and traditional dissections of the same heart specimen. However, this was not without potential limitations. First, the relatively small number of included cases compared with other cardiac anatomy studies performed on preserved specimens alone might limit our findings; hence, a larger sample size would be preferred. Second, because the clinical history of 27.5% of our donors is unknown, it might be possible that some of them presented with greater than mild tricuspid regurgitation. Third, although the use of endoscopes allowed us to obtain real-time, functional footage of the right atrioventricular leaflet function together with scallops and commissures, these images could not be calibrated accurately for direct measurements. Finally, following reanimation, these hearts were perfusion fixed using a 40 to 50 mm Hg pressure of 4% paraformaldehyde pH-buffered solution to fix the chambers and vessels in an approximation of each heart being in an end-diastolic state. This preservation technique, coupled with the potential for edema during the reanimation process, may result in a distortion of the myocardial structure and ventricular chamber size but should not affect the valve structure analyzed in this study.

CONCLUSIONS

The human right atrioventricular valve seldom has only 3 leaflets: both functional commissures and/or the presence of a functional fourth leaflet make them more anatomically complex. Moreover, there are no significant differences in the overall annular sizes between valves eliciting different leaflet/commissure configurations. All right atrioventricular leaflets may be divided into scallops by indentations, and the techniques used here highlighted the presence of functional scallops in some cases. The inferomural region was consistently the most variable area of right atrioventricular valve.

We consider that our unique observations relative to the right atrioventricular valve functional anatomy will provide important insights for those developing or deploying percutaneous therapies for the treatment of right-sided structural heart diseases. Anatomic studies such as that presented here are critical for educating both device designers and physicians to ensure optimal patient outcomes for right atrioventricular valve procedures.

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PERSPECTIVES

WHAT IS KNOWN? It has been conventional wisdom that the right atrioventricular valve has 3 leaflets.

WHAT IS NEW? Our unique functional anatomy study shows that the human right atrioventricular valve seldom has only 3 leaflets. The presence of a fourth leaflet and commissure in 42.5% of hearts significantly changes the geometry of the valve and should be taken into account while developing and performing right valve regurgitation repair procedures.

WHAT IS NEXT? Future studies that focus on developing devices and procedures aimed at the right atrioventricular valve should be conducted in the context of the true, functional anatomy of this valve.

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KEY WORDS tricuspid valve, quadricuspid valve, right atrial appendage, right atrium, tricuspid regurgitation, valve leaflet

APPENDIX For supplemental videos, please see the online version of this paper.