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ORIGINAL ARTICLE

Morphometry and aberrant morphology of the adult human tricuspid valve leaflets

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Abstract The tricuspid valve complex has been studied since the beginning of the twentieth century, and variations in the structural orientation of the tricuspid leaflets has been reported before, as the occurrence of accessory leaflets poses a major problem during surgeries related to the tricuspid valve. In this study, 36 adult formalin-fixed human hearts were analyzed to compare the number, form and size of the tricuspid leaflets. The result shows that in right ventricles, the number of leaflets can vary from the routine three to as many as seven, and the localization of such accessory leaflets of the tricuspid valve differs between specimens. Five leaflet forms were the most common, and the 'typical' form of tricuspid valves with no accessory leaflets was only present in a small percentage of the cases studied. Measurements of the main and accessory leaflets showed that the anterior leaflets were the largest, followed by the inferior leaflets, while the septal and the accessory leaflets were the smallest in size. On the basis of these results, it is suggested that three leaflets of the tricuspid valve are relatively uncommon, with frequent occurrences of accessory leaflets. The multicuspidal form of the tricuspid valve therefore raises concern about understanding the functional and physiological significance of the accessory leaflets.

Keywords Tricuspid valve · Accessory leaflets · Papillary muscles · Chordae tendineae · Human heart

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Introduction

The atrioventricular complex of the right ventricle comprises the orifice, leaflets, supporting chordae tendineae of various types and papillary muscles (Rogers and Bolling 2009). The atrioventricular orifice of the right ventricle is guarded by the tricuspid valve, and it is described as comprising three leaflets, from which the name 'tricuspid' is derived. The leaflets are considered to be the primary units of the tricuspid valve, separated from each other by a commissure and meeting centrally when closed. These leaflets are located septally, anterosuperiorly and inferiorly, corresponding to the marginal sector of the atrioventricular orifice (Standring 2009). Each leaflet is basally confluent with the fibrous connective tissue of the atrioventricular orifice, arranged to continue marginally on its ventricular aspect with the diverging fascicles of the tendinous cords, which adhere to the papillary muscles on the ventricular wall (Silver et al. 1971; Standring 2009). The leaflets of the tricuspid valve have been reported to show variability in their structural attachment and number, and the occurrence of accessory leaflets is a known phenomenon (Sutton et al. 1995; Skwarek et al. 2004). According to Skwarek et al. (2007), four accessory leaflets were the most common, with the existence of eight-leaflet forms. Silver et al. (1971) and Piccoli et al. (1979) investigated the constitution of the valve leaflets and showed differences in their structure, arrangement and morphology. It has also been suggested that the number of leaflets in the tricuspid valve increases in an evolutionary line, but the rules of division for the main leaflet remain unknown (Skwarek et al. 2004). The variations in the structure, position and chordal attachment of the main as well as accessory leaflets therefore are still relatively unexplored, especially in terms of the anatomical morphology and subsequent physiological functions.

Transthoracic echocardiography, used to visualize the ventricles of the heart, only facilitates two-dimensional visualization of the valve. Thus, the complex three-dimensional structure of the tricuspid valve with the presence of accessory leaflets can pose a major problem during associated surgeries and complications arising because of a discrepant morphological estimation of the tricuspid valve between the preoperative two-dimensional transthoracic echocardiography and direct surgical visualization have been reported (Anwar et al. 2006). Furthermore, the presence of accessory valve leaflets not only complicates surgeries as accessory valves are prone to prolapse (Yoon et al. 2008). Morphological studies, estimating the number of leaflets with their measurements, can therefore be beneficial for the development of future methodological techniques. Many congenital cardiac anomalies include accessory valve tissues, and complications arising because of such accessory tissue have been described in rare conditions such as Ebstein's anomaly, tetralogy of Fallot and coarctation of the aorta (Motabagani 2006; Paranon and Acar 2008; Xanthos et al. 2011).

Thus, the main aim of this study was to compare the morphology of the three main adult human tricuspid valve leaflets and accessory leaflets; to objectively determine the number and localization of the main and accessory leaflets; and to analyze their size by measuring the base and height of the main and accessory leaflets.

The findings from this study can be useful for cardiac surgeons who rely on direct morphological estimations of the right atrioventricular region. Furthermore, absolute measurements of the leaflets can aid in the development of the bioprosthetic valves used for tricuspid repair.

Materials and methods

This study was carried out at the Department of Anatomy at Sikkim Manipal Institute of Medical Sciences, India, on 36 adult cadaveric human hearts (26 male and 10 female) without malformation or pathological changes. All the specimens collected were from individuals who had died from non-cardiovascular diseases and were between 30 and 65 years of age. The hearts were non-macerated and preserved by immersion in 4 % neutral formalin, then dissected.

Dissection of the specimens

Cadaveric hearts were opened following the path of blood flow from the orifice of the inferior to the superior vena cava and along the right margin of the right ventricle. The sternocostal surface of right ventricle was drawn aside to study the internal features of the right atrioventricular valve. The number of leaflets, their localization and measurements of the base and height of each leaflet were determined using a graduated vernier caliper (0–100 mm). The attachments of the leaflets with the chordae and papillary muscles were also noted, and the specimens were photographed using a high-resolution digital 12-megapixel Zeiss camera.

Identification of the commissure

Precise criteria were used to identify the commissure, which enabled firm identification of the main and accessory leaflets. The marking points for the commissure were the chordae tendineae, which branched in a fan-like manner with a short stem. Such chordae arose exactly from the apex of the papillary muscles and were attached to the free margins of the

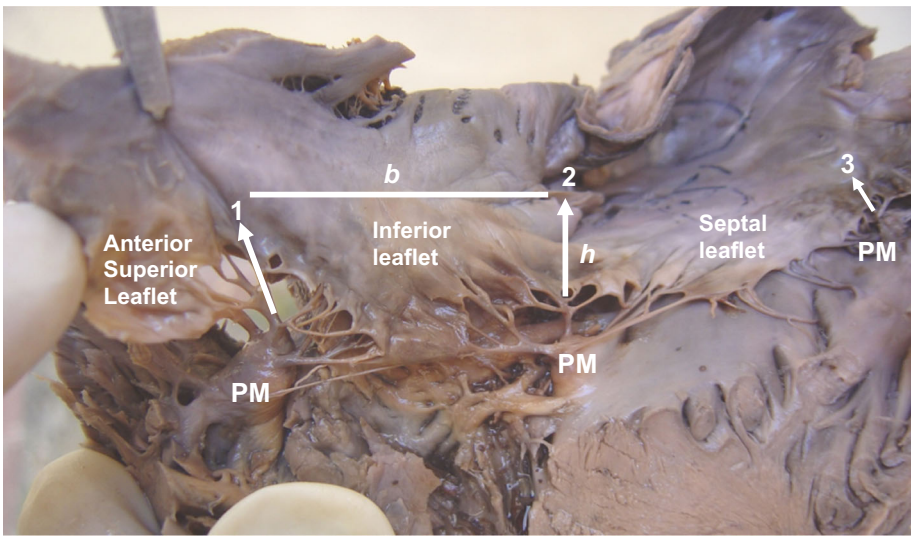

Fig. 1 Typical three-leaflet form of the tricuspid valve showing the anterior-superior (anterior), inferior and septal leaflets. The three leaflets are separated by the commissure, identified as the precise point where the chordae branch in a fan-like manner with a short stem; such chordae arise from the apex of the papillary muscles (PM). *White arrows* show the commissure: *arrow 1* shows the anteroinferior, *arrow 2* the inferoseptal and *arrow 3* the anteroseptal commissure. '*b*' in the figure shows the base and '*h*' the height of the inferior leaflet

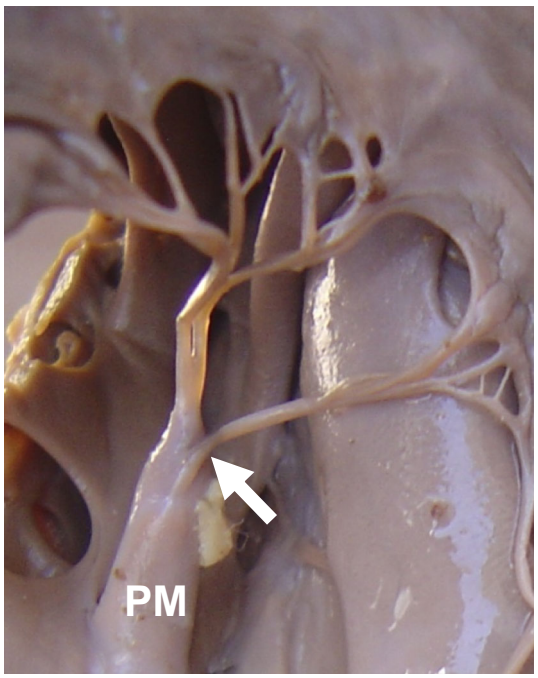

Fig. 2 A magnified view of the fan-shaped chordae tendineae arising from the apex (*arrow*) of the papillary muscle (PM)

leaflets. Based on the attachment of the chordae to leaflets and the papillary muscles, three commissures were identified and named the anteroinferior, inferoseptal and anteroseptal commissure (Figs. 1, 2). Depending on the depth of the indentations by the chordal attachment, the commissure was distinguished from clefts and notches which usually subdivides the leaflets into smaller scallops or a promontory of the major leaflets (Fig. 6).

Identification of leaflets

Three leaflets can generally be distinguished in the tricuspid valve complex. The anterosuperior leaflet is the largest of all three leaflets and is located anterosuperiorly to the atrioventricular junction on the superolateral aspect of the supraventricular crest, ending at the anteroinferior commissure (Fig. 1). The septal leaflet is usually located between the anteroseptal and inferoseptal commissure at the location of the atrioventricular node, which lies at the apex of the triangle of Koch. The inferior leaflet is located along the diaphragmatic surface of the atrioventricular junction between the anteroinferior and inferoseptal commissure (Fig. 1). Furthermore, the anterosuperior leaflet is always attached to the anterior papillary muscle, which is also the largest of the three papillary muscles (Fig. 1). The base of the anterior papillary muscle is attached to the anterolateral ventricular wall below the anteroinferior commissure. The posterior or inferior papillary muscle is attached to the inferior leaflet along the inferoseptal commissure. The septal papillary muscle is the smallest of all three, arises from the septomarginal trabeculae (moderator band) and is attached via its chordae to the septal leaflet. The identification of the leaflets and papillary muscles was done as described by Standring (2009). However, the relative position and attachment of the three leaflets to the papillary muscles can be altered by the presence of accessory leaflets. Such accessory leaflets have been reported to be present between the main leaflets (Skwarek et al. 2004, 2007) and arise between the three main commissures, gaining their terminal attachment via the chordae to either the apex of the main papillary muscle or the apex of the supernumerary (aberrant) papillary muscles. Based on the attachment of the accessory leaflets via the chordae to the papillary muscles, the accessory leaflets were considered to be independent of the major leaflets.

Measurements of the base and height of leaflets

The height '*h*' of the leaflets was considered to be the minimum vertical distance of the commissure, which ranged from the attachments of the fan-shaped chordae on the papillary muscles to the fibrous collagenous rim of the atrioventricular orifice (Fig. 1). The base '*b*' of the leaflets was defined, according to Williams et al. (1995), as the horizontal distance between the two commissures, which was measured along the fibrous collagenous rim of the atrioventricular orifice (Fig. 1).

Results

Morphology of leaflets

Gross examination of the human tricuspid valve showed that it possessed a triangular orifice bound by a collagenous rim to which the tricuspid leaflets, namely the anterosuperior, inferior, septal (Fig. 1) and accessory leaflets (Figs. 3, 4, 5), were attached. Direct visual analysis of the size of leaflets showed that the anterosuperior (anterior) leaflets were always the largest component of the tricuspid valve. In a closed position, the anterosuperior leaflets were attached mainly to the atrioventricular junction on the posterolateral aspect of the supraventricular crest, and the anterosuperior leaflets extended along the membranous septum between the anteroinferior and the anteroseptal commissure. Accessory leaflets were present between the commissures. The septal leaflets were observed to be the smallest in size and were attached from the inferoseptal commissure on the posterior ventricular wall across the muscular septum, angled across the membranous septum to the anteroseptal commissure. The inferior leaflets were intermediate in size, mural in attachment along the

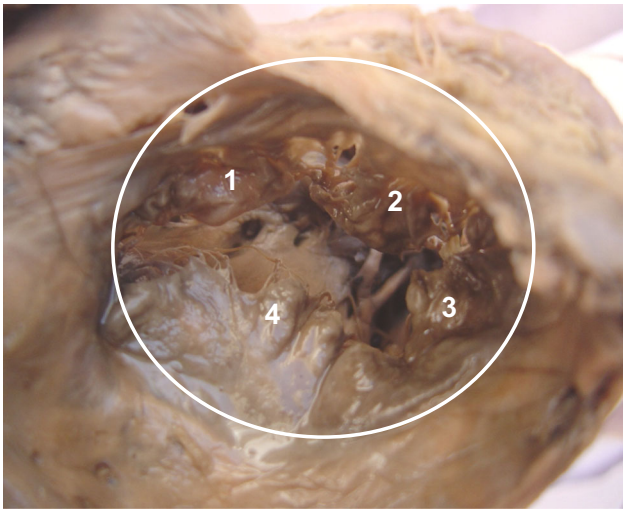

Fig. 3 Aerial view of the atrioventricular orifice (*in a closed form*) along with an accessory leaflet. The above figure shows: *1* the septal leaflet, *2* anterosuperior leaflet, *3* accessory leaflet, *4* inferior leaflet

diaphragmatic surface of the atrioventricular junction, and were limited by the inferoseptal and anteroinferior commissure. It was found that accessory leaflets between the main commissure were also attached by its fan-shaped chordae to the apex of the own papillary muscles, the apex of the adjacent papillary muscles or the apex of the accessory papillary muscles. Accessory leaflets were different from the scallop of the main leaflet, as it was observed that the commissure and depth of the indentation made by the chordae were well demarcated in the main leaflets. Scallops in a few specimens were seen to be directly adherent to the ventricular wall (Fig. 6).

Estimations of the number of leaflets showed that the most common type was the five-leaflet form (Fig. 4), consisting of three main and two accessory leaflets. This form of leaflet appeared in 34.3 % of the total specimens studied. Furthermore, the greatest number of leaflets found was seven, which existed in 16.6 % of the specimens (Fig. 5; Table 1).

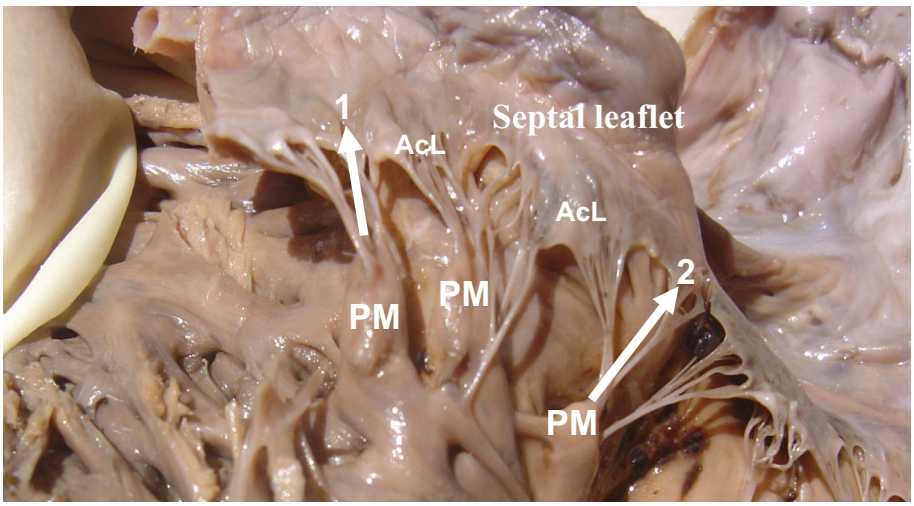

Fig. 4 Two accessory leaflets (AcL) shown between the anteroseptal (*arrow 1*) and inferior septal (*arrow 2*) commissure (*white arrow* shows the commissure). *PM* in the figure indicates papillary muscles, along with an accessory papillary muscle. Note the chordae arise from the apex of the main as well as accessory papillary muscles

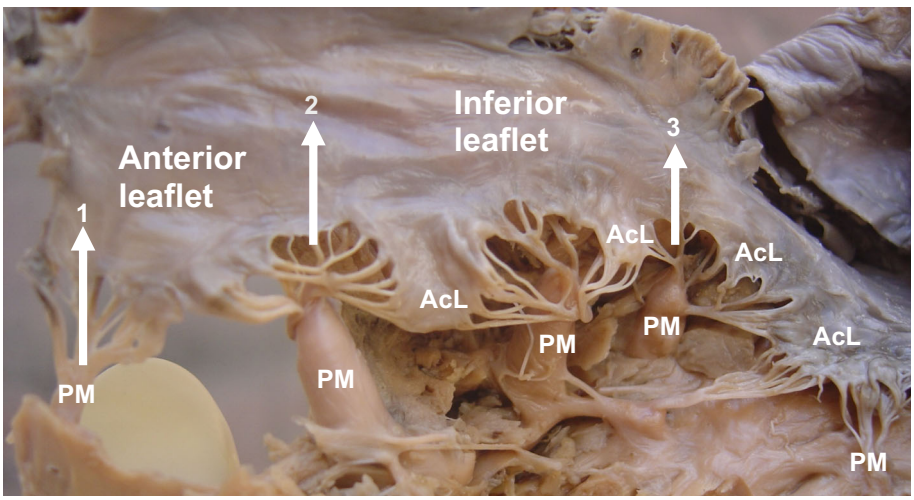

Fig. 5 Accessory leaflets (AcL, four in number) located between the anteroseptal (*arrow 1*) and anteroinferior (*arrow 2*) commissure and between the anteroinferior (*arrow 2*) and inferoseptal (*arrow 3*) commissure. Note: Papillary muscles (PM) are more than three in number. *AcL* accessory leaflets

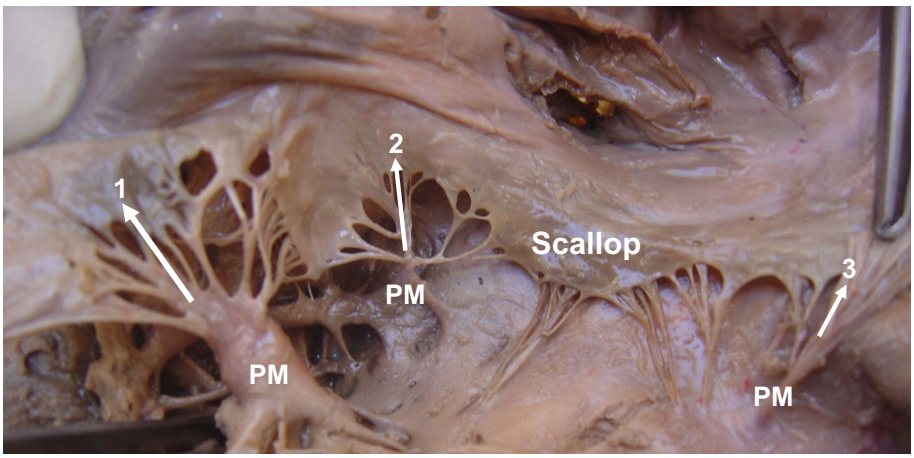

Fig. 6 Scallop located between the inferior and septal leaflet; the chordae of the scallop attach directly to the ventricular wall. *Arrow 1* shows the anteroinferior commissure, *arrow 2* shows the inferoseptal commissure, and *arrow 3* shows the anteroseptal commissure. *PM* papillary muscles

Depending upon the localization, it was observed that accessory leaflets were present between the inferoseptal and anteroseptal commissure in 19.4 % of the specimens (Figs. 5, 7; Table 2). Accessory leaflets between the anteroinferior and inferoseptal commissure were the rarest and were only found in 13.8 % of cases (Fig. 3; Table 2), while accessory leaflets between the anteroinferior and anterospetal commissure were the most common and occurred in 50.0 % of the specimens. The most important observation was that the 'typical' form of the tricuspid valve with only three main leaflets was present only in 16.6 % of cases studied (Tables 1, 3).

Measurements of the leaflets

A vernier caliper (in millimeters) was used to measure the base '*b*' and height '*h*' of the anterosuperior, inferior, septal and accessory leaflets (Fig. 1). The shapes of all four types of leaflets were triangular. The measurement of the anterosuperior (anterior) and septal leaflet in particular showed the base was longer than the height. The relationship between the base and height of the inferior and accessory leaflet varied. The measurements of all the main and accessory leaflets were noted, and the height of the anterosuperior leaflet was observed to be greatest, followed by the height of the inferior and septal leaflets. Accessory leaflets were always the shortest in height, but only a few millimeters smaller than the septal leaflets. The measurement of the base of the leaflets also showed that the anterior, inferior and septal leaflets were always broader in size than the accessory leaflets.

The mean measurement of the height of the anterior leaflets was 21.21 ± 0.95 mm, of the inferior leaflets was 20.03 ± 0.75 mm, of the septal leaflets was 15.04 ± 0.82 mm and of the accessory leaflets was 12.02 ± 0.65 mm. The mean measurement of the base of the anterior, inferior, septal and accessory leaflets was 38.01 ± 14.03, 32.03 ± 10.05, 34.01 ± 9.05 and 25.02 ± 6.01 mm, respectively (Table 3).

Furthermore, differences in the attachments of the tendinous cords were also observed, and three types of chordal attachment were found to be prevalent. The first type of chordae attached to the apex of only one papillary muscle, the second type of chordae attached to the apex of two papillary muscles, and the third type was adherent to either the bases or sides of the adjacent papillary muscles. The second and third types of chordal attachment were the most common and most seen among the posterior and anterior groups of papillary muscles. Occurrences of accessory papillary muscles were observed along with the leaflets, and most of them were found to be attached along the septal wall.

Table 1 Frequency of occurrences of different types of tricuspid leaflets

Different number of leaflets present in the right ventricles (total number of specimens, $n = 36$)	Total number of leaflets in % ($n = 36$)
3	16.6
4	8.3
5	34.3
6	25.0
7	16.6

Discussion

This study shows the importance of morphological variation of the tricuspid valve leaflets. Results from this study show the variability in the structure, size and number of the tricuspid valve leaflets. Most of the specimens studied showed a more than three leaflet form, while only 16.6 % of the specimens examined showed the typical three tricuspid leaflets. The sizes of the accessory leaflets were

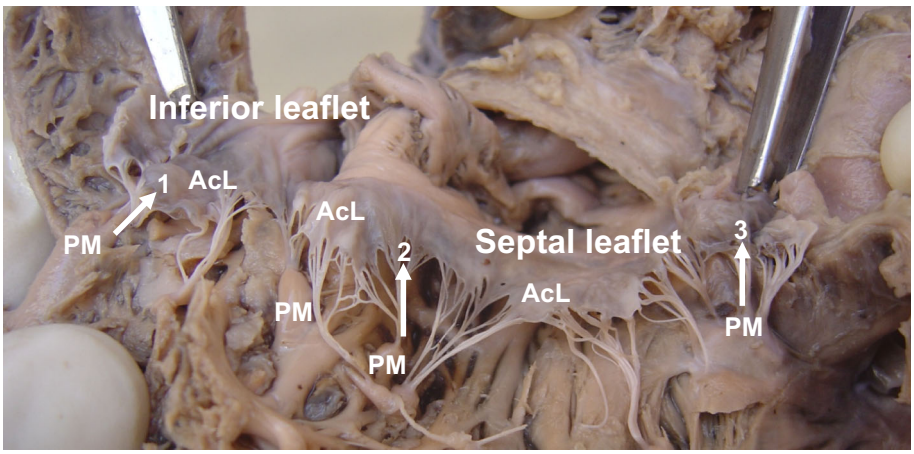

Fig. 7 Three accessory leaflets (AcL) located between the anteroinferior (*arrow 1*), inferoseptal (*arrow 2*) and anteroseptal commissure (*arrow 3*), forming a six-leaflet form. *PM* papillary muscle

Table 2 Frequency of the occurrence of accessory leaflets

Location of the accessory leaflets	Number (n) of accessory leaflets found (n = 30/36 cases)	Frequency of the occurrence of leaflets in the total number (n = 36) of specimens studied (%)
(1) Between the anteroinferior and inferoseptal commissure	5	13.81
(2) Between the inferoseptal and anteroseptal commissure	7	19.40
(3) Between the anteroinferior and anteroseptal commissure	18	50.0

always observed to be smaller than the main leaflets, and the greatest number of leaflets was found to be seven (by count). Accessory leaflets were mainly localized between the anteroinferior and anteroseptal commissure and were found in 50 % of the specimens. The attachment of the chordae tendineae varied along with anomalous occurrences of the papillary muscles and leaflets.

In the past, the tricuspid valve was regarded to be bicuspid; hence, it was considered to be similar to the mitral valve (Victor and Nayak 1994). However, today it is known that the tricuspid valve has septal, anterosuperior and inferior (or mural) leaflets, respectively. Furthermore, there is no solitary zone of apposition for the leaflets as seen in the case of the mitral valve. Embryological studies done on the development of valve leaflets in terminated pregnancies show that the tricuspid valve develops equally from the endocardial cushions and myocardium, and the leaflets of the atrioventricular valves are formed by a process of delamination of the inlet zones of the right ventricles (Lamers et al. 1995). Thus, the tricuspid valve depicts numerous indentations and variations of the leaflet material along with its chordae and papillary muscles (Xanthos et al. 2011). The classical image of the tricuspid valve consisting of three leaflets could therefore be encountered less often, and such variations in the structure of the tricuspid valve have been reported before (Silver et al. 1971; Sutton et al. 1995; Skwarek et al. 2004, 2007). In a study done by Swarek et al. (Table 3), three-leaflet forms were reported to be present in only 9.3 % of the cases studied, four-leaflet forms in 36.15 %, five-leaflet forms in 33.3 %, six-leaflet forms in 13.3 % and seven-leaflet forms in 4.1 %. The accessory leaflets were localized between the inferior and septal leaflets in 25.3 %, between the anterior and septal leaflets in 9.3 % and between the anterior and inferior leaflets in 5.3 %. In another study by Lukaszewska et al. (1970) on 130 human hearts (Skwarek et al. 2004), it was reported that the three-leaflet forms appeared only in 8.46 % of the specimens and the four-leaflet forms in 36.15 %. The accessory leaflets were localized between the inferior and septal leaflet in 23.8 %, between the anterior and septal leaflet in 7.8 % and between the anterior and inferior leaflet in 4.5 %. The five-leaflet form appeared in 33.85 %, six leaflets appeared in 17.69 %, and both seven and eight leaflets appeared in 1.53 % of the cases. The results from this study are thus consistent with the previous observations and show the occurrence of three- to seven-leaflet forms. In this study, we also report the absolute measurements for the size of the leaflets, with accessory leaflets being the smallest in size, but adequately large to be considered as functional leaflets.

The results from this and many other studies show that defining anatomically normal number of tricuspid leaflets can be difficult, raising an important concern for cardiothoracic surgeons who rely on the routine tricuspid leaflet arrangement for the surgical decision-making process. Although it can be debated whether two-dimensional

Table 3 Comparisons of the various features of the tricuspid leaflet according to the present study and that of Skwarek et al. (2004)

	Number of leaflets in %					Height '*h*' of the leaflets (mean ± SD)				Base '*b*' of the leaflets (mean ± SD)			
	Three (%)	Four (%)	Five (%)	Six (%)	Seven (%)	AL (mm)	IL/PL (mm)	SL (mm)	AcL (mm)	AL (mm)	IL (mm)	SL (mm)	AcL (mm)
Present study ($n = 36$)	16.6	8.3	34.3	25.0	16.6	21.21 ± 0.95	20.03 ± 0.75	15.04 ± 0.82	12.02 ± 0.65	38.0 ± 14.0	32.0 ± 10.0	34.0 ± 9.0	25.0 ± 6.0
Skwarek et al. (2004) ($n = 75$)	9.3	36.1	33.3	13.3	4.1	23.88 ± 0.85	21.35 ± 0.90	18.33 ± 0.98	14.88 ± 0.99	Not measured	Not measured	Not measured	Not measured

AL anterosuperior leaflets, *IL/PL* inferior/posterior leaflets, *SL* septal leaflets, *AcL* accessory leaflets

transthoracic echocardiograms and magnetic resonance imaging are helpful in assessing tricuspid valve function, to a great extent the morphology of the tricuspid valve remains unclear because of discrepant measurements of the tricuspid valve, which are routinely reported between preoperative two-dimensional echocardiography and direct surgical visualization (Tager et al. 1998). It is also well known that the incidence of right-side endocarditis increases along with intravenous drug abuse (Moss and Munt 2003; Panduranga et al. 2013), altering the arrangement and morphology of the tricuspid leaflets. Such anomalous distribution of the tricuspid valve leaflets changes the normal physiological functions as the valve leaflets may not fully open or close accordingly and thus play a significant role in the development of tricuspid regurgitation, promoting valve diseases and subsequently heart failure (Behm et al. 2004).

Therefore, it is reasonable to state that the morphological estimation of the tricuspid valve is important for related surgeries and may prove to be of vital significance for surgical or other innovative procedures currently under trial.

To conclude, our results suggest that the emergence of accessory leaflets is of common occurrence, and further studies on the mechanisms behind the appearance of such accessory leaflets are required from developmental genetics, physiological, functional and clinical points of view. Furthermore, the relatively common occurrence of accessory leaflets not only has surgical implications, but brings up the question of why an anatomically stationary number of three leaflets is increasingly uncommon. Understanding the tricuspid valves can be important for cardiac surgeries that involve partial transfer of the inferior (posterior) leaflets of the tricuspid valve, tricuspid replacement, valvuloplasty and prolapse of the valves.

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Conflict of interest None

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