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The connection between the papillary muscles and leaflets of the tricuspid valve

M. Skwarek[1], M. Dudziak[2], J. Hreczecha[3], M. Grzybiak[3]

[1]*Department of Sports Medicine and Hygiene, the Jędrzej Śniadecki Academy of Physical Education and Sport, Gdańsk, Poland*
[2]*Non-invasive Cardiovascular Diagnostic Unit, Institute of Cardiology, Medical University, Gdańsk, Poland*
[3]*Department of Clinical Anatomy, Medical University, Gdańsk, Poland*

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The tricuspid valve is more differentiated during evolutionary development than the mitral valve. In birds it is a muscular structure joined directly to the papillary muscles, although the mitral valve of birds resembles that of mammals. There have been well-known studies describing the evolutionary line of connection of the tricuspid valve with the papillary muscles.
The present study was performed on a group of 107 formalin-fixed adult human hearts. The valves and papillary muscles were classified according to a scheme for human hearts drawn up earlier. The types of connection between leaflets of the tricuspid valve and the papillary muscles were classified according to a scheme drawn up earlier for vertebrates. We observed 3 types of connection between leaflets of the tricuspid valve and the papillary muscles in the group studied. The muscular and membranous connections were not linked with any one type of tricuspid valve. Atypical forms of distribution of the tendinous chords of the right ventricle were observed. It was found that valves with a higher number of leaflets were (with the exception of type 0) provided with a smaller number of tendinous chords.
Atavistic features and atypical forms of distribution of the tendinous chords are present in a small percentage of samples of the human right valvular apparatus.

Key words: tricuspid valve, papillary muscles, tendinous chords, morphology, human heart

INTRODUCTION

One of the oldest pictures of the tricuspid valve is found in *De Humanis Corpori Fabricia* written by Vesalius in the 16th century. Despite the many anatomical studies made of the tricuspid valve, rapid progress in the field of interventional cardiology and cardiosurgery [5–7, 10, 19, 23] has created a constant demand for research into this structure. The evolutionary line of the tricuspid valve is more differentiated than that of the mitral valve. The tricuspid valve of birds is a muscular crescent-shaped structure connected directly to the papillary muscles, while the mitral valve resembles that of primates [15, 24–26].

Traditional textbooks of anatomy and anatomical nomenclature treat the papillary muscles as homogenous structures. Grochowski [11] studied the papillary muscles of the right ventricle and introduced the concept of multi-apical and multi-segmental papillary muscles. Multi-apical papillary muscles are, according to Grochowski, muscles with more than one point from which the tendinous chords grow. He describes multi-segmental papillary muscles as apparently separate muscles lying on one wall of the ventricle. According to the hypothesis of Szostakiewicz-Sawicka and Grzybiak [25], the papillary muscles migrated during evolution along the walls of the right ventricle as the tricuspid valve changed from being crescent-shaped to its present form. A septomarginal trabecule developed during this migration.

Address for correspondence: J. Hreczecha, Department of Clinical Anatomy, Medical University of Gdańsk, Dębinki 1, 80–211 Gdańsk, Poland, tel./fax: +48 58 349 14 20, e-mail: chanastra@interia.pl

The types of connection between the tricuspid valve and the papillary muscles have changed during phylogenesis from straight to membranous connections and then to tendinous chords, as reflected in the ontogenesis [1, 2, 24, 25]. The well-known relationship between the geometry and function of the right ventricle [3] and the atavistic features of the tricuspid valve [22] indicates that research is required into the atavistic features of the connection between this valve and the papillary muscles. There has been no qualitative analysis of these but the occurrence of these forms was noted in older textbooks of anatomy, although not referred to in newer ones [4, 28, 29, 31].

Surgical repair of the mitral valve using the tissue of the tricuspid valve and its subvalvular apparatus has increased in frequency as a result of the lower rate of complications associated with it in comparison with the use of synthetic materials. Surgical repair of the mitral and tricuspid valves is performed simultaneously using the de Vega method or, in the case of stenosis, the balloon-plastic method.

In our study the distribution of tendinous chords in tricuspid valves was examined with regard to other atavistic types of connection of the tricuspid valve to the papillary muscles.

MATERIAL AND METHODS

The study material consisted of a group of 107 formalin-fixed adult human hearts (30 female and 77 male) aged between 18 and 90 years in which no macroscopic developmental failures or pathological changes had been found. The hearts were taken from the collection of the Department of Anatomy of the Medical University of Gdańsk, Poland.

The hearts were opened from the side of the right atrium, the line of the cut running from the ostium of the superior cardinal vein to the right atrioventricular ostium. The right chambers were opened with a V-shaped cut along the right margin and across the anterior wall of the right ventricle.

The valves were divided into types and subtypes depending on the number of leaflets and the location of accessory leaflets [14, 20–22] (Fig. 1). The papillary muscles of the right ventricle were classified according to an earlier scheme [11, 21] (Fig. 2). The types of connection leaflets between the tricuspid valve and the papillary muscles were classified according to a scheme drawn up earlier for vertebrates [24, 27]. Connection type 1, typical for birds, was a straight connection between the leaflet and the papillary muscles, type 2 was a membranous connection recorded in the literature as characteristic for many primates [25, 26] and type 3 took the form of tendinous chords.

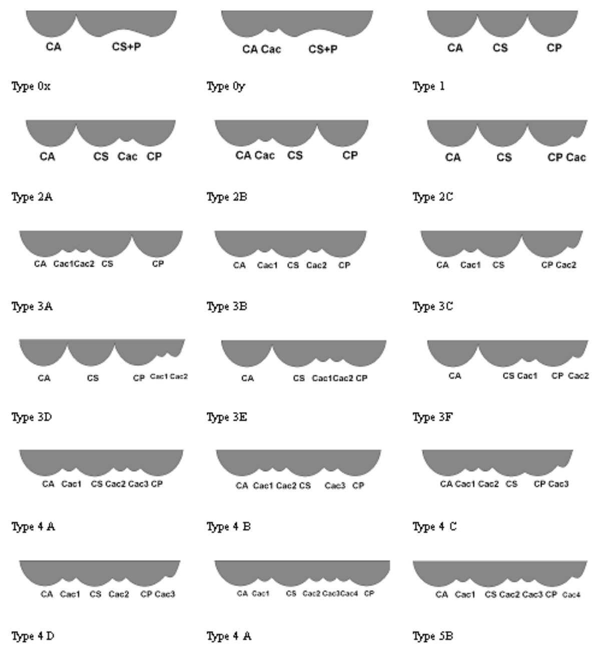

Figure 1. Classification of the tricuspid valve according to [14, 20–22].

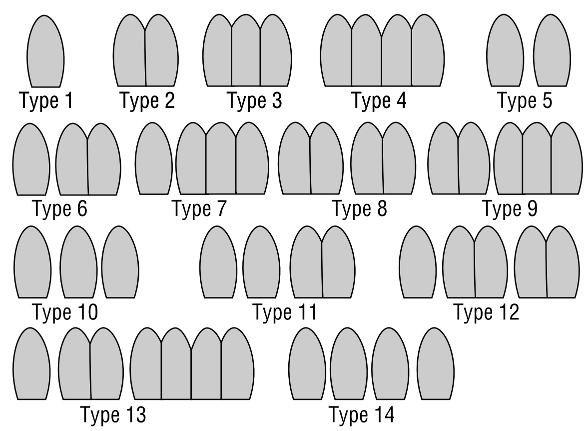

Figure 2. Classification of the papillary muscles according to [11].

RESULTS

As mentioned above, three types of connection between the leaflets of the tricuspid valve and the papillary muscles were observed in the group studied. The incidence of each particular type of connection is presented below.

Type 1 — muscular connections

Straight connections (Fig. 3) between leaflets of the tricuspid valve and the papillary muscles were found in 33 of the 107 hearts studied (30.27%). Of these valves

Figure 3. A straight connection between tricuspid valve and papillary muscle. The arrow shows the straight connection of a leaflet of the tricuspid valve to the papillary muscle.

Table 1. Straight connection between papillary muscle and tricuspid valve

Occurrence of straight connection in the hearts studied	30.27%
Attaching to one leaflet	81.82%
Attaching to 2 leaflets	18.18%
Attaching to anterior papillary muscle	52.63%
Attaching to posterior papillary muscle	5.26%
Attaching to septal papillary muscle	3.25%

Table 2. Membranous connection between papillary muscle and tricuspid valve

Occurrence of membranous connection in the hearts studied	6.54%
Attaching to one leaflet	28.57%
Attaching to more than one leaflet	71.43%

the connection was present in one of the leaflets in 27 of the 33 hearts (81.82%) and in 2 of the leaflets in 6 of the hearts (18.18%). In total 57 connections of this type were found. Of these 22 (38.59%) originated from the anterior papillary muscles, 30 (52.63%) from the posterior papillary muscles, 3 (5.26%) from the septal papillary muscles and 2 (3.52%) from muscle of the posterior angle of the right ventricle (Table 1).

Type 2 — membranous connections

Membranous connections between the tricuspid valve and papillary muscles were present in 7 of the 107 hearts studied (6.54%) (Table 2). Perforations in the membranous connection were examined. Multiple membranous connections, in the anterior, posterior and septal leaflets, were observed in 5 hearts, while in 2 hearts they were singular. Figure 4 shows examples of membranous connections. Figure 4A shows a membranous connection between the anterior leaflet of the tricuspid valve and the septal papillary muscle, the membrane giving a tendinous chord to the septal leaflet, while Figure 4B shows this type of connection between the posterior leaflet of the tricuspid valve and the septal papillary muscle. Perforations of the membranous connections are visible in both photographs.

Type 3 — tendinous chords

The distribution of tendinous chords in the tricuspid valve was studied. Apart from patterns

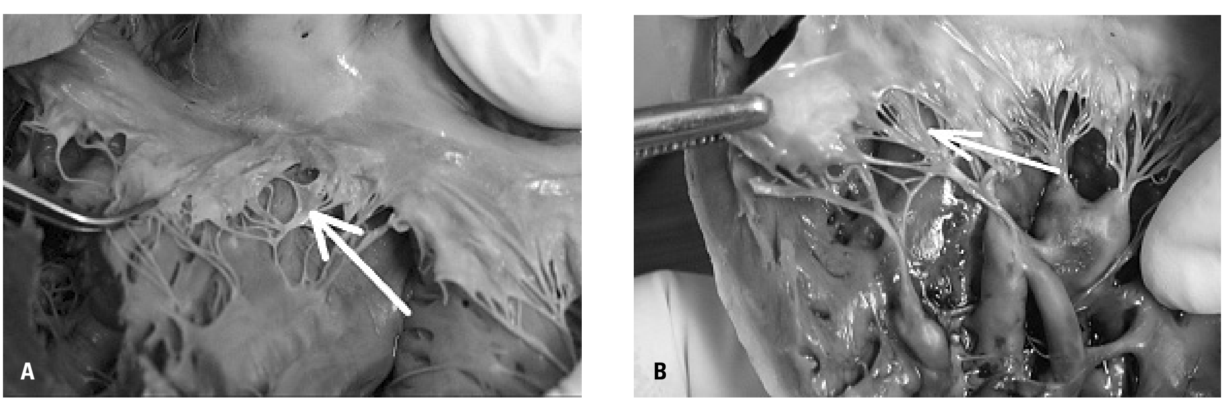

Figure 4. A membranous connection between tricuspid valve and papillary muscles. Arrows show the membranous connection of leaflets of the tricuspid valve to the papillary muscles.

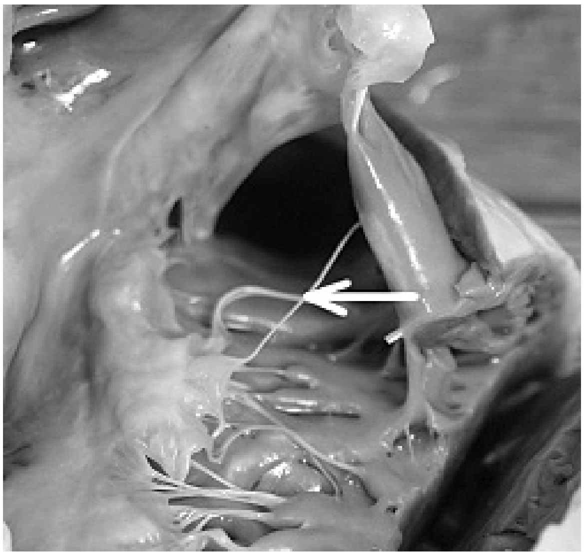

Figure 5. An unusual form of connection between the septal leaflet of the tricuspid valve and the anterior papillary muscle. The arrow shows a tendinous chord arising from the anterior papillary muscle attaching to the septal leaflet of the tricuspid valve. This chord grows from the trunk of the papillary muscle and not as it usually does from the apex of the muscle.

described in the classical textbooks of anatomy, we observed other rarer forms which we decided to take as the starting point for the analysis. Figure 5 shows a connection between the septal leaflet of the tricuspid valve with the anterior papillary muscle. A tendinous chord grows up from the central part of the muscle. Figure 6 shows another atypical origin of the tendinous chords, a septomarginal trabecule. The first atypical tendinous chord connects the septomarginal trabecule with the septal leaflet, while

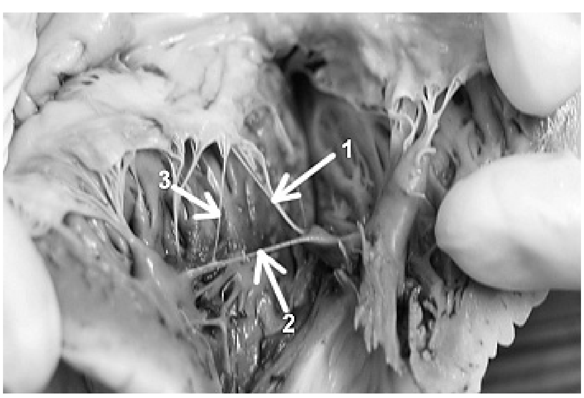

Figure 6. An unusual form of distribution of tendinous chords in the right ventricle. A tendinous chord arising from the septomarginal trabecule attaches to the septal leaflet of the tricuspid valve (1) and another spurious tendinous chord joins the trabecule to the posterior papillary muscle (2). A further tendinous chord arises from the above-mentioned spurious tendinous chord and attaches to the septal leaflet of the tricuspid valve (3).

Table 3. Tendinous chords of the right ventricle

Leaflet	Mean	SD
Main	20.79	15.91
Accessory	8.14	4.85
Anterior	22.07	7.55
Posterior	16.08	7.08
Septal	24.24	8.44

the second atypical spurious tendinous chord connects the trabecule with the posterior papillary muscle. A further atypical tendinous chord arises from the spurious tendinous chord referred to and joins the septal leaflet of the tricuspid valve.

The number of tendinous chords was studied in relation to particular leaflets of the tricuspid valve. The main leaflets usually received 20.79 ± 8.43 chords and the accessory cusps 8.14 ± 4.85 chords. We then determined the number of tendinous chords in particular main leaflets. The anterior leaflets usually received 22.07 ± 7.55 chords, the posterior 16.08 ± ± 7.08 and the septal leaflets 24.24 ± 8.44 of chords (Table 3). Statistical analysis with the χ^2 test showed that the probability of septal leaflets receiving the highest number of chords was 95%, while this was lowest for the posterior leaflet.

The tricuspid valves were divided according to an earlier classification [14, 20]. The average numbers of tendinous chords attaching to valves were as follows: 70.45 ± 15.91 in type 1, 64.42 ± 13.50 in type 2, 60.85 ± 15.18 in type 3, 51.88 ± 9.57 in type 4 and 48.66 ± 9.19 in type 5. The numerical range of tendinous chords supplying a tricuspid valve ranged from 39 (one type 1 and one type 4A valve) to 106 (type 3B valve) (Table 4). On analysis of tricuspid valve type 0 we found an average of 25 ± 3 chords in the anterior leaflets and 38.67 ± 5.51 in the posteroseptal leaflets. With the exception of type 0,

Table 4. Distribution of tendinous chords in particular types of tricuspid valve

Type of valve	Mean	SD
1	70.45	15.91
2	64.42	13.5
3	60.85	15.18
4	51.88	9.57
5	48.66	9.19

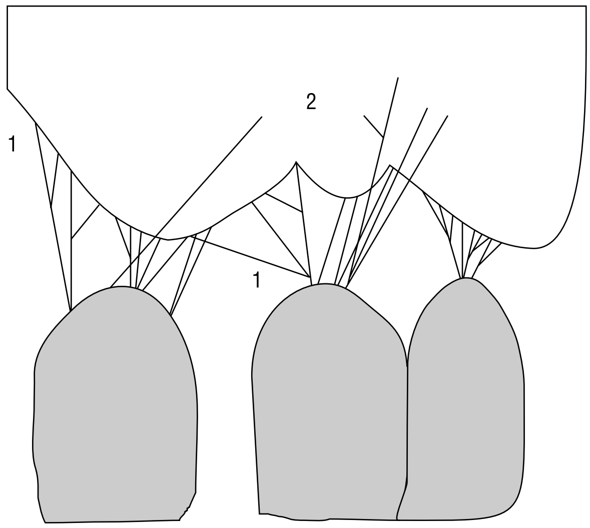

Figure 7. Primary (1) and secondary (2) tendinous chords. The primary chords attach to the margin of the leaflet and the secondary to the ventricular surface of the valve.

the number of tendinous chords tends to diminish as the number of leaflets increases.

The next step in the investigation was to study the number of tendinous chords attaching to the margin of leaflets and to the ventricular surface of it (Fig. 7). The number of tendinous chords attached to the margin of the anterior leaflet was 13.05 ± 4.9, while 8.84 ± 4.33 attached to the ventricular surface. The margin of the posterior leaflet received an average of 10.75 ± 5.14 chords and the ventricular surface an average of 5.25 ± 3.59 chords. The number of chords attached to the margin of the septal leaflet was on average 15.21 ± 5.95, with 8.78 ± 4.01 attached to the ventricular surface. The average number of tendinous chords attached to the margin of the main leaflets was 13.01 ± 5.64 with 7.62 ± 4.41 attached to the ventricular surface, while the number attached to the margin of the accessory leaflets was 5.32 ± 2.98 with 2.98 ± 2.68 attached to the ventricular surface. More tendinous chords attached to the margins of leaflets than to the ventricular surface and this was confirmed by statistical analysis using the χ^2 test ($p < 0.05$). The quotients of chords attaching to the margin of the leaflet to those attaching to the surface of the valve were as follows: 1.48 for anterior leaflets, 2.05 for posterior leaflets, 1.73 for septal leaflets, 1.72 for main leaflets and 1.98 for accessory leaflets (Table 5).

DISCUSSION

The tricuspid valve is more differentiated during evolutionary development than is the mitral valve [15]. Well-known studies have been performed describing the evolutionary line of the connection of the tricuspid valve to the papillary muscles [25]. We studied the different modes of connection and found the following three types, which represent the evolutionary line of this connection: type 1 — a straight connection, type 2 a membranous connection and type 3 a connection by means of tendinous chords.

Table 5. Distribution of primary and secondary tendinous chords in particular types of leaflet

Leaflet	Primary tendinous chords		Secondary tendinous chords	
	Mean	SD	Mean	SD
Main	13.01	5.64	7.62	4.41
Accessory	5.32	2.98	2.98	2.68
Anterior	13.05	4.9	8.84	4.33
Posterior	10.75	5.14	5.25	3.59
Septal	15.21	5.95	8.78	4.01

The first type was present in 30.27% of the group studied. Of the valves containing this type of connection 81.82% showed it in one leaflet and 18.18% in two leaflets. A total of 57 connections were found of this type. The posterior papillary muscles were most often connected directly with the tricuspid valve (52.63%). Direct connections originating from the anterior papillary muscles were rarer (38.59%), and the least common were direct connections joining the septal papillary muscles (5.26%) and the muscles of the posterior angle of the right ventricle (3.52%) with the tricuspid valve. This kind of connection between papillary muscles and tricuspid valve has been described in other primates by Szostakiewicz-Sawicka [26], who failed to find it in human hearts, although the group of human hearts studied was small and the hearts were only a control in the study of tricuspid valve anatomy in other vertebrates.

The membranous connections between the papillary muscles and the tricuspid valve occurred in 6.54% of the group studied. These were also described by Szostakiewicz-Sawicka [26] but without detailed quantitative analysis. In the course of her study Szostakiewicz-Sawicka [25, 26] worked out a theory for the evolution of the connection between the papillary muscles and the leaflets of the tricuspid valve, according to which tendinous chords are the perfected form of the connection. The most primitive form is the direct connection, while membranous connections are an intermediate stage in the evolutionary process. Szostakiewicz-Sawicka also noticed that the membranous connections are often perforated.

The next question we considered was the number of tendinous chords in particular leaflets of the tricuspid valve. Understanding the distribution of tendinous chords may be useful with regard to tricuspid valve replacement, rebuilding the subvalvular apparatus after rupture from various causes [5, 6, 23] and transplantation of the tricuspid valve [7]. Study of the tendinous chords performed on the animal model of the mitral valve [12, 19] has shown the complexity of this problem. Research reporting the relationship between the geometry and function of the right ventricle has usually taken the form of electrophysiological reports [3] and has neglected the morphology of the tendinous chords supplying the tricuspid valve. Study of the morphology of the tendinous chords may also be regarded as well-founded in the light of research performed *in vivo* on animals, which has shown that the tension exerted on chords anchored in the margins of leaflets is different from that exerted on chords providing ventrical part of the cusps [16]. This subject, studied by Lomholt, has been discussed by Duran [8], who underlined the importance of knowledge of the morphology of the tendinous chords with respect to mitral valve replacement with the problem of remaining insufficiency. Duran's study also describes the function of the tendinous chords of the left ventricle from a historical point of view. The article is enhanced by a reproduction of a picture by Leonardo da Vinci showing the tendinous chords. It is interesting that da Vinci described the chords as anchored in the margins of leaflets with the word "prima". The same term for this kind of chord was used by an anatomist of our own time to distinguish them from the "secondary" chords which provide the ventrical part of the cusps [4, 25, 26].

Defects, especially subclinical defects, of the tricuspid valve are becoming increasingly detectable with the development of echocardiography. Repair and prosthesis of the valve are also related to the tendinous chords and the geometry of the right ventricle. This is the reason why, in describing types of connection between the papillary muscles and the tricuspid valve, we have also drawn attention to the morphology of the tendinous chords.

In the group studied the anterior leaflet received an average of 22.07 chords, the posterior 16.06 chords and the septal 24.24 chords. An average of 20.79 tendinous chords anchored to main leaflets, while accessory cusps received an average of 8.14 chords. Szostakiewicz-Sawicka [26] in her study obtained the following results: the anterior leaflet received an average of 30 chords, the posterior 37 chords and the septal 57.2. There were fewer chords in our study than in that of Szostakiewicz-Sawicka. However, the author pointed out that in drawing up these results she had included the tendinous chords of accessory leaflets with those of the main leaflets according to which wall the accessory cusps were attached. The following results were obtained by Łukaszewska-Otto [17]: the anterior leaflet was supplied by 28 chords, the posterior by 23 and the septal by 40. In this study the analysis of the number of tendinous chords in the accessory cusps was performed by means of topographic division with numbers ranging from 8.49 to 15.5 chords, higher therefore than our results. In our study as well as those of Szostakiewicz-Sawicka [26] and Łukaszewska-Otto [17] there is a tendency towards similarity in the proportions between the number of tendinous chords in particular leaflets of the tricuspid valve, with the largest number of chords in the septal cusp and the lowest in the posterior leaflet and more than double the number of tendinous chords attached to the main leaflet than to accessory leaflets. The fact that the septal leaflets, which are not the largest, are supplied by the greatest number of chords, may be related to the fact that they are the least mobile, as has been borne out in electrophysiological and radiological studies [13, 31].

The distribution of tendinous chords attaching to the tricuspid valve was also studied by Wafae et al. [30], who distinguished two types of the tricuspid valve, those with and those without accessory leaflets, the average number of tendinous chords in valves without accessory leaflets being 18.25 and that in valves with accessory leaflets 22.56. This author did not specify the number of tendinous chords in main and accessory leaflets and so we cannot compare our results unambiguously with his. In our study and in the others cited this distinction was introduced and showed significant differences between main and accessory cusps. Wafae et al. [30] divided accessory leaflets into two groups, namely accessory leaflets and commissural cusps, a division which we have not followed. The word "commissure" does not exist in anatomical nomenclature but has been introduced by surgeons after effective operation on mitral stenosis, and used in repairing the tricuspid valve [9, 18]. Because of the lack of demonstrable homology between accessory leaflets in different types of valves, we treated all accessory leaflets as a single group without dividing them into groups based on location as other authors have done [17].

In studying the number of tendinous chords in particular types of tricuspid valve we have observed differences between types of tricuspid valve.

Our results are lower than those of Szostakiewicz--Sawicka [26], according to whom the number of tendinous chords is in the range of 90 to 138 with an average of 125.8. This difference may be caused by the age of the hearts studied. In another study [24] this author analysed the number of tendinous chords in different age groups, from foetuses to the elderly, showing significant differences between particular groups. In terms of the number of tendinous chords our results are similar to results of Szostakiewicz--Sawicka [24] for hearts aged from 39 to 52 years. The quotients of chords attaching to the margin to the number of chords attaching to the surface of valve were similar in our study to those obtained by Szostakiewicz-Sawicka [24].

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