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Anatomy of the left ventricular subvalvular apparatus of the Eurasian wild boar (*Sus scrofa* L.)

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SUMMARY

Xenotransplantation consists in transplanting an organ from one species into another. Although the greatest challenges in heart transplantation are currently associated with immunology, the search should begin with the basic science of comparative anatomy of animals.

The Eurasian wild boar (*Sus scrofa*) is an ancestor of the domestic pig (*Sus domestica*) and an invasive species currently not covered by European protection programmes. The growing Eurasian wild boar population is a pool of potential organ donors, and is also a useful subject of research in comparative animal anatomy and other areas of zoology.

The research material consisted of 71 Eurasian wild boar hearts. Following the methodology described by Kustrzycki et al. (2000), the number of bellies of the papillary muscles of the left ventricle and the type of connection between the muscles and the left ventricle wall were determined. In addition, the height of departure of the muscle from the ventricular wall was determined, the morphological regularity of the papillary muscle was assessed, and the tendinous cords extending from the papillary muscles were examined.

Analysis of the material showed similarities and differences in the anatomy of the hearts of Eurasian wild boar in comparison with various other species. The research broadens knowledge of the comparative and normal anatomy of the myocardium in the suborder Suina in comparison with selected individuals of other species.

KEY WORDS: Animal anatomy, heart, *Sus scrofa*, subvalvular apparatus, papillary muscle

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INTRODUCTION

The dynamic development of cardiac surgery has made it possible for patients to recover from severe heart disease. Heart transplants, the most advanced cardiac surgery, face a significant obstacle, i.e. an inadequate supply of organs. The solution to this problem may be xenotransplantation, i.e. the transplantation of animal organs into humans. On 7 January, 2022, scientists from the University of Maryland Medical Center announced to the public that they were the first in the world to successfully transplant a heart taken from a genetically modified domestic pig into a human patient (Reardon, 2022). This achievement has the potential to open up new therapeutic opportunities for patients with severe cardiovascular disease. Diseases of the human circulatory system are one of the most common causes of death in all parts of the world. The subject of transplantation must be addressed as an element of public health (WHO, 2020). In the context of organ transplantation in humans, knowledge of the basic sciences of normal and comparative anatomy should be used to analyse the structure of mammals, in accordance with the motto '*Sanitas animalium pro salute homini*'.

Heart defects associated with the mitral valve are among the most common. Regurgitation of this valve may lead to other, secondary heart conditions such as left atrial hypertrophy, due to regurgitation of blood. In addition, mitral regurgitation may be associated with a number of congenital malformations, such as left heart hypoplasia syndrome or subvalvular aortic stenosis. Modern medicine has not yet found a better method of treating valve diseases, such as artificial or biological valve transplants, so it is important to learn about the anatomical structure of the basal apparatus of various animal species in order to expand the possibilities of future xenotransplantation, thereby protecting public health (Hall and Guyton, 2011).

The similarity of genomes makes the domestic pig a very useful species for biomedical research, especially concerning xenotransplantation (Aigner et al., 2010). The growing clinical demand for good-quality biological heart valves of animal origin has led to the need for research on the subvalvular apparatus of various animal species.

Commonly used in biomedical research, the domestic pig (*Sus domestica*), a species of domesticated animals valued in many parts of the world, has a wild ancestor, the Eurasian wild boar (*Sus scrofa* L.). In Europe, it is an invasive species with 'least concern' status on the list of the International Union for Conservation of Nature (IUNC, 2019). The genetic similarity, even identity, of domestic pig and Eurasian wild boar, is the inspiration for comparative anatomical studies of the subvalvular apparatus of the heart. Apart from the scientific knowledge contributed by these studies, the results may provide information with practical applications, including the potential for xenotransplantation.

The aim of this study is to compare the structure of the subvalvular apparatus in the left side of the heart of Eurasian wild boar, humans, and other animal species.

It was hypothesized that learning about the anatomy of the subvalvular apparatus of the left side of the boar's heart can reveal a potentially important source of material for xenotransplantation, in addition to providing original morphological data that broaden the scope of knowledge in the field of comparative animal anatomy.

MATERIALS AND METHODS

The study was performed on 71 Eurasian wild boar (*Sus scrofa* L.) hearts, showing no pathological changes visible to the naked eye. The animals were of both sexes, with carcass weight of 42-56 kg. The material was obtained from hunting. The specimens were not damaged in any way by gunshots. The left ventricle was opened with one incision along the left ventricular edge (*margo ventricularis sinister*), and the ventricular cavity was irrigated under running water and analysed.

Following the methodology described by Kustrzycki et al. (2000), the number of bellies of the papillary muscles of the left ventricle and the type of connection of the papillary muscles with the wall of the left ventricle were determined. Three types of connections have been distinguished: basal, in which the papillary muscle is attached to the wall of the ventricle only at its base; intramural, in which the papillary muscle is almost completely connected to the wall of the ventricle; and mixed, in which the papillary muscle partially adjoins the wall of the ventricle. The height of the departure of the papillary muscles from the ventricular wall was determined as well. For this purpose, a line was drawn from the valve annulus to the apex of the heart, which made it possible to define the height of the papillary muscle exit site as high, medium or low. In addition, the general morphology of the entire papillary muscle, its symmetry and cohesiveness were assessed.

The tendinous cords extending from the papillary muscles were also examined. The number tendinous cords departing from the papillary muscles and then their number at the point of attachment to the rough zone of the valve were determined. In addition, the number of tendinous cords extending from the subauricular and subatrial papillary muscle to the parietal cusp and septal cusp was determined. The false tendons extending from the subatrial and subauricular muscle to the septum and to the heart wall and those connecting the two papillary muscles were counted as well.

Photographs were taken with a Samsung Galaxy S10e (Samsung Group, South Korea) and then graphically edited.

RESULTS AND DISCUSSION

The left atrium (*atrium cordis sinistrum*) and the left ventricle (*ventriculus sinister*) have a less complex anatomical structure than the right side of the heart. The left atrium captures oxygenated blood, passing it on, while the left ventricle is tasked with distributing blood to further body tissues (Anderson, 2012). One of the four heart valves, the mitral valve (*valva atrioventricularis sinistra s. valva bicuspidalis s. valva mitralis*), is present in the left atrioventricular orifice (*ostium atrioventruculare sinistrum*) connecting the two chambers. It consists of the septal cusp (*cuspis septalis*) of the valve and the wall cusp (*cuspis parietalis*) of the valve. From the cusps, tendinous cords (*chordae tendineae*) connect these cusps with the papillary muscles, while false tendinous cords (*chordae tendineae falsae*) do not connect with the valve. In the case of the left ventricle, the subauricular papillary muscle (*musculus papillaris subauricularis*) and the subatrial papillary muscle (*musculus papillaris subatrialis*) were distinguished (Fig. 1). It is worth noting the columnae carneae (*trabeculae carneae*) (Fig. 2) and septomarginal trabecula (*trabecula septomarginalis*) on the wall of the left ventricle, which are functionally associated with the cardiac conduction system (*Nomina Anatomica Veterinaria,* 2017).

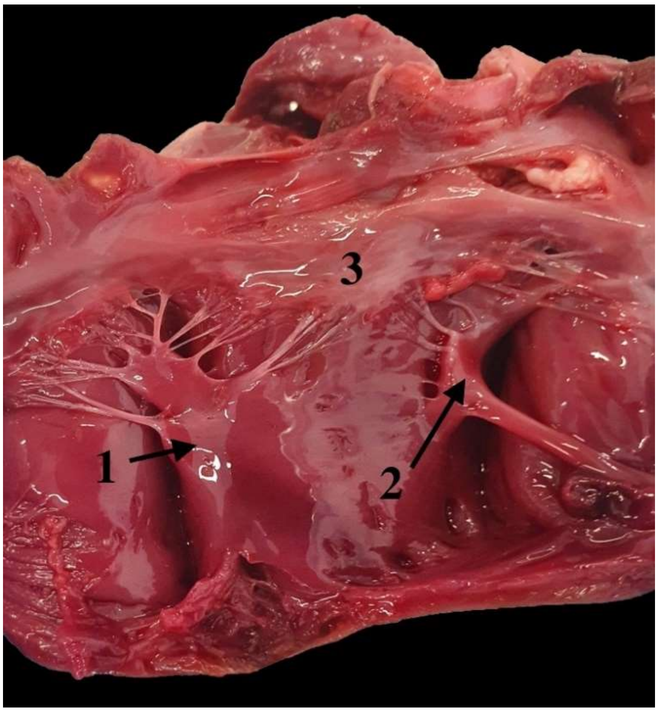

Fig. 1. 1. Subauricular papillary muscle (single, mixed type); 2. Subatrial papillary muscle (single, intramural type); 3. Mitral valve anterior cusp

The left atrioventricular valve of the human, domestic pig and Eurasian wild boar consists of two cusps – a wall cusp and a septal cusp. The location and size of these cusps are very similar; the wall cusp accounts for two thirds of the circumference of the entire valve (Crick et al., 1998). There are also differences between the pig species and humans, primarily at the microstructural level, as noted by Lelovas et al. (2014). They differ in metalloproteinase I expression and proteoglycan distribution. Like the valve cusps, the papillary muscles in the left ventricle show similarities in number and topography. The papillary muscle bellies were evaluated and classified on the basis of their macroscopic structure.

The mean height of the subatrial muscle's departure from the ventricular wall was classified as high in 12,7% of specimens, medium in 83,1% and low in 4,2%. For the subauricular muscle, the results were as follows: high 57,7%; average 42,3%; low 0%. This study showed that the subauricular muscle is usually one degree of height lower than the subatrial muscle, with only three of 71 specimens (4,2%) deviating from this rule.

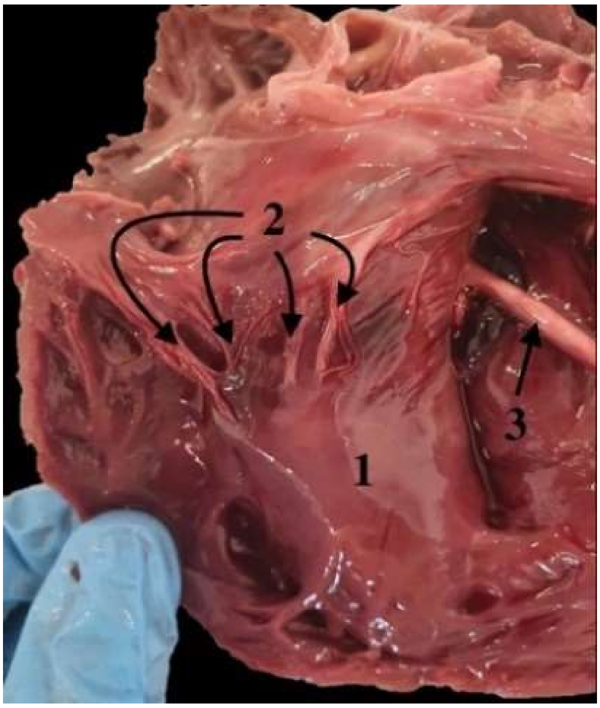

Fig. 2. 1. Subauricular single-belly papillary muscle; 2. Tendinous cords connecting the subauricular muscle with the mitral valve; 3. Muscle trabeculae (*trabeculae carneae*)

Regarding the number of bellies of the subatrial muscle, the most common were hearts with a three-bellied muscle (49,3%) or a two-bellied muscle (43,7%), while the least common were hearts with a single belly, with a frequency of 7%. In the case of the subauricular muscle, three-bellied muscles were predominant (46,5%). Hearts with three-bellied muscles accounted for 39,4% and single-belly muscles for 14,1%.

The mode of attachment of the papillary muscle to the ventricular wall of the myocardium was determined. The basal mode of attachment of the subatrial papillary muscle was detected in 29 hearts, the intramural type in 20, and the mixed type in 22. The proportions were similar for the subauricular muscle: basal in 30 hearts, intramural in 12 hearts, and mixed in 29.

As reported by Bochenek and Reicher (2022), the left ventricle of the human heart has two papillary muscles, one anterior (*anterior*) and one posterior (*posterior*). The muscles are more developed than in the right ventricle and are of similar size. *Nomina Anatomica Veterinaria* (2017) also recognizes this nomenclature for domestic animals. Typically, the anterior muscle has one major muscle group, while the posterior muscle has two or three major muscle groups (Rajiah et al., 2019). In humans, this is confirmed in a comparative study by Ozbag et al. (2005), but the animal hearts studied (dogs, sheep, and goats) were reported to have only one belly. Our research and that of other authors (Ateş et al., 2017) indicates that the Eurasian wild boar may have more than one muscle belly. Among other taxonomic groups of animals, examples of animals with more than one muscle belly can be found in the class Aves (birds), such as the common ostrich (*Struthio camelus*). It has three papillary muscles in the left ventricle, two on the lateral wall, and one connecting to the septum of the cardiac muscle (Figueroa and Henriquez-Pino, 2009).

The anatomical structure of the tendinous cords connecting the papillary muscles and the valve cusp are as shown in Tables 1, 2 and 3.

Table 1

Tendinous cords extending from the papillary muscles of the left ventricle

Number of tendinous cords	Subatrial muscle		Subauricular muscle	
	Number of hearts N = 71	%	Number of hearts N = 71	%
5	-	-	1	1,4
6	-	-	6	8,5
7	4	5,6	11	15,5
8	6	8,5	10	14,1
9	12	16,9	15	21,1
10	12	16,9	9	12,7
11	15	21,1	11	15,5
12	11	15,5	1	1,4
13	5	7,0	4	5,6
14	4	5,6	2	2,8
15	2	2,8	1	1,4

Mundra (2018) found that more cords arise from the anterior papillary muscle in humans. The number of tendinous cords emerging from the apex of the anterior papillary muscle ranged from 6 to 21 (mean = 12,45; median = 12). The number of tendinous cords that emerged from the posterior papillary muscle ranged from 3 to 22 (mean = 9,67; median = 10). In our study of the Eurasian wild boar, the number of tendinous cords emerging from the subauricular muscle, corresponding to the human anterior muscle, ranged from 1 to 15 (mean = 6,45; median = 6; mode = 1), while the range for the subatrial muscle, corresponding to the human papillary muscle, was 2-15 (mean = 9; median = 11; mode = 4,12). The number and morphology of the tendinous cords, which directly affect the motility of the valve and mitral cusps, may significantly impact coaptation of the cusps during left ventricular contractions. Damage to these cords, degeneration or other dysfunctions can lead to the development of functional mitral valve regurgitation, as mentioned by Di Mauro et al. (2013). However, these are not the only causes of this disease.

Table 2

Tendinous cords extending from the subatrial muscle to individual mitral valve cusps

Number of tendinous cords	Parietal cusp		Septal cusp	
	Number of hearts N = 71	%	Number of hearts N = 71	%
1	-	-	4	5,6
2	10	14,1	24	33,8
3	2	2,8	21	29,6
4	11	15,5	19	26,8
5	21	29,6	2	2,8
6	9	12,7	1	1,4
7	8	11,3	-	-
8	9	12,7	-	-
9	1	1,4	-	-

Table 3

Tendinous cords extending from the subauricular muscle to individual mitral valve cusps

Number of tendinous cords	Parietal cusp		Septal cusp	
	Number of hearts N = 71	%	Number of hearts N = 71	%
1	-	-	6	8,5
2	10	14,1	25	35,2
3	4	5,6	15	21,1
4	11	15,5	12	16,9
5	23	32,4	2	2,8
6	17	23,9	8	11,3
7	3	4,2	3	4,2
8	3	4,2	-	-

Ozbag et al. (2005) report that the domestic dog (*Canis familiaris* L.) may have 5-10 tendinous cords extending from the subauricular muscle and 5-13 from the subatrial muscle. In domestic sheep (*Ovis aries* L.), the corresponding range is 3-8 for both papillary muscles, and in the domestic goat (*Capra hircus* L.) 4-10 for the subauricular muscle and 3-11 for the subatrial muscle.

The total number of tendinous cords reaching the rough zone in all European wild boar hearts ranged between 100 and 250. Most of the hearts, 63,4%; contained from 130 to 190 of these tendinous cords, among which the largest group (18,3% of the total number) had 150-160 cords. In the remaining 36,6% of hearts, the number of cords was in the range of 100-130 or 190-250, of which the least common were those with 110-120 or 240-250 tendinous cords, i.e. one heart (1,4%) each. Detailed data for each papillary muscle are given in Table 4.

Table 4

Tendinous cords departing from the rough zone for each papillary muscle

Number of tendinous cords	Subatrial muscle		Subauricular muscle	
	Number of hearts N = 71	%	Number of hearts N = 71	%
<60	6	8,5	6	8,5
60-70	9	12,7	12	16,9
70-80	10	14,1	19	26,8
80-90	15	21,1	15	21,1
90-100	17	23,9	7	9,9
100-110	3	4,2	7	9,9
110-120	2	2,8	3	4,2
120-130	7	9,9	1	1,4
130-140	2	2,8	-	-
140-150	-	-	1	1,4

The rough zone, which is present in both valve cusps, is widest in the lowest part of the leaflet, tapering on the perimeter. It acts as a border between the anterior and posterior cusps of the mitral valve. The remainder of the valve, shown in Fig. 3, is the smooth zone (Di Mauro et al., 2013).

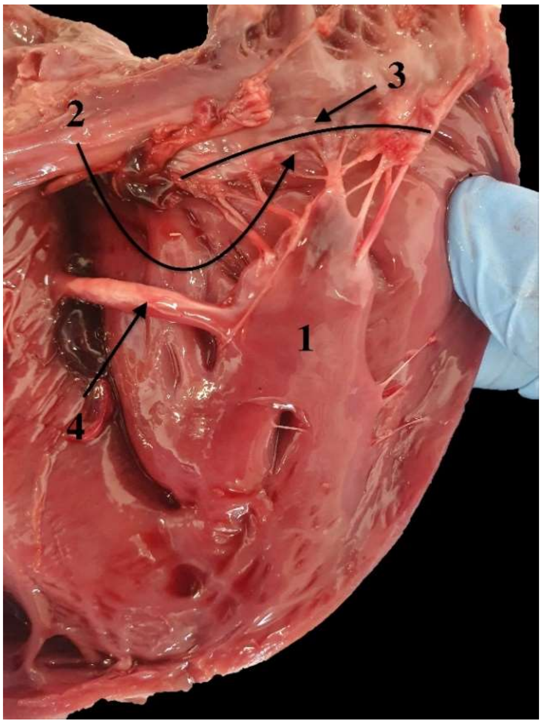

Fig. 3. 1. Subatrial papillary muscle; 2. Rough zone; 3. Smooth zone; 4. Muscle trabeculae (*trabeculae carneae*)

In all specimens, false tendons were observed connecting the papillary muscles with the interventricular septum, the ventricular wall, and/or the papillary muscles. The papillary muscles of 66 hearts were not connected by false tendons. Two hearts showed a connection between the subauricular and subatrial muscle in the form of one false tendon, and three had two false tendons. None of the hearts showed a connection with the three tendinous cords. False tendons extending from the subatrial muscle to the interventricular septum appeared singly or doubly in most hearts. There were no false tendons extending from that papillary muscle to the ventricle wall in 53,5% of specimens, while false tendons extending from the subauricular muscle to the interventricular septum and the ventricular wall were absent in more than half of the examined material. In the remaining specimens, they were mainly single. This is presented in detail in Table 5.

Table 5

Number of false tendons extending from the subatrial and subauricular muscles to the interventricular septum or to the ventricular wall

Number of false tendons	Subatrial muscle				Subauricular muscle			
	to the septum		to the wall		to the septum		to the wall	
	Number of hearts n = 71	%	Number of hearts n = 71	%	Number of hearts n = 71	%	Number of hearts n = 71	%
0	11	15,5	38	53,5	39	54,9	57	80,3
1	26	36,6	23	32,4	22	31,0	11	15,5
2	19	26,8	8	11,3	7	9,9	3	4,2
3	10	14,1	2	2,8	3	4,2	0	0,0
4	4	5,6	-	-	-	-	-	-
5	1	1,4	-	-	-	-	-	-

This research was based on anatomically normal Eurasian wild boar hearts, but there are reports that organs affected by heart defects may not have false tendons. An analysis by Philip et al. (2011) revealed that among 68 hearts of malformed piglets, as many as 38,2% had no false tendons. Left ventricular false tendons have also been shown to cause a functional murmur, known as an innocent murmur (Gardiner and Joffe, 1991).

CONCLUSIONS

All the hearts had two papillary muscles, cords, and false tendons. Among the subatrial papillary muscles, three-belly muscles were predominant, while single-belly muscles were the least common, found in only 7% of hearts. In the case of the subauricular muscle, two bellies were most common. In both the subauricular and subatrial muscles, the predominant type of connection with the ventricle of the myocardium was the basal type. Statistically, more tendinous cords departed from the subauricular muscle than from the subatrial muscle. The Eurasian wild boar has similar numbers of tendinous cords (1-15) as sheep (3-8) and domestic goats (3-11), but fewer than humans (3-22). Most tendinous cords, irrespective of the type of papillary muscle, extended to the wall cusp of the mitral valve. The most common terminal attachment for the false tendons was the myocardial septum. As other authors have not performed such detailed anatomical measurements of the subvalvular apparatus as in our study of wild boar hearts, a detailed and comprehensive comparison of our research with results described in the literature is not possible. Knowledge of the morphology of the papillary muscles and tendinous cords of animals is considered to be fundamental, given the current trend of using mammalian hearts as models for xenotransplantation research. Research on the comparative anatomy of animals may in the future increase the available pool of species of potential use for immunologists and as organ donors, which is in the interest of public health.

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