

Anatomical and clinical aspects of the papillary muscles

Anatomiczne i kliniczne aspekty mięśni brodawkowatych

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Słowa kluczowe: mięśnie brodawkowe, zmienności anatomiczne, struny ścięgliste.

Abstract

Papillary muscles, as components of the subvalvular apparatus, play a crucial role in the proper functioning of the heart valves. Although the most commonly encountered variants can be classified traditionally, it is essential to remember that there is significant variability in their number, structure, and shape. This variability is not without clinical significance – specific papillary muscle variants translate into different prognoses, therapeutic approaches, and surgical procedures. Therefore, in our study, we conducted an analysis of available literature to determine which papillary muscle variants are most common, what their vascular supply is, and what the significance of individual variants is in daily clinical practice. To achieve this, we searched popular scientific databases such as PubMed, Google Scholar, and Scopus, using keywords such as papillary muscles, clinical aspects of papillary muscles, anatomical variability of papillary muscles, and papillary muscle rupture – as one of the most common clinical situations related to papillary muscles. This paper presents the results of our review – organised and accompanied by a table.

Streszczenie

Mięśnie brodawkowe jako elementy aparatu podzastawkowego odgrywają kluczową rolę w prawidłowym funkcjonowaniu zastawek serca. Mimo że najczęściej spotykane są warianty anatomiczne zgodne z klasycznym podziałem, należy pamiętać, że występuje znaczna zmienność w zakresie ich liczby, struktury i kształtu. Zmienność ta nie pozostaje bez znaczenia klinicznego – specyficzne warianty mięśni brodawkowatych przekładają się na odmienne rokowanie, podejście terapeutyczne oraz mają znaczenie w planowaniu i wykonywaniu procedur chirurgicznych. W związku z tym w naszej pracy przeprowadzono analizę dostępnego piśmiennictwa w celu określenia, które warianty anatomiczne mięśni brodawkowatych występują najczęściej, jakie jest ich unaczynienie oraz jak konkretne warianty przekładają się na codzienną praktykę kliniczną. W tym celu przeszukano popularne naukowe bazy danych, takie jak PubMed, Google Scholar i bazę Scopus, przy użyciu słów kluczowych, takich jak mięśnie brodawkowe, aspekty kliniczne mięśni brodawkowatych, zmienność anatomiczna mięśni brodawkowatych oraz pęknięcie mięśni brodawkowatych – jako jedna z najczęstszych sytuacji klinicznych związanych z mięśniami brodawkowatymi. Publikacja ta w formie uporządkowanej i opatrzonej tabelami przedstawia rezultaty naszej pracy.

Introduction

Papillary muscles are components of the cardiac muscle chambers that play a crucial role in the proper opening and closing of atrioventricular valves. Through contraction, they maintain the proportions between the valve annulus and the heads of the papillary muscles, preventing valve leaflets from prolapsing [1].

In the right ventricle of the heart, 3 papillary muscles with varying degrees of development are generally distinguished. The anterior papillary muscle is located on the anterior wall of the chamber, being the largest and exhibiting the most regular occur-

rence. The inferior papillary muscle emerges from the posterior wall, often forming 2 or 3 muscular cones. The septal papillary muscle is the smallest and displays the greatest variability, often divided into multiple smaller papillary muscles originating from the anterior part of the septal wall [2, 3].

In the left ventricle of the heart, 2 papillary muscles are identified, being better developed than those in the right ventricle. This is directly attributed to the necessity of generating greater force to keep the mitral valve leaflets in place during the contraction of the left ventricle, where higher pressure prevails. The superior papillary muscle is situated at

the lateral boundary of the anterior wall of the chamber, while the inferior papillary muscle arises from the posterior (infero-basal) wall near the septal wall. Both muscles are roughly the same size and supply both leaflets of the mitral valve [4].

Integral components of papillary muscles are chordae tendineae – thick collagen and elastin fibres serving as connections between valve leaflets and papillary muscles. They enable the transmission of the muscle contraction force to the valve. Chordae tendineae are typically classified into primary (marginal), secondary (intermediate), and tertiary (basal). This classification is based on the connection between the heads of papillary muscles and the valve leaflets. Primary chordae tendineae attach to the free edge of the valve leaflets, while secondary chordae connect the papillary muscles to the middle part of the ventricular surface of the valve leaflets. Tertiary chordae attach directly to the ventricular wall or to the other papillary muscles [5, 6].

The classification of anatomical variations of papillary muscles is an essential aid in the planning and execution of cardiothoracic procedures, as well as in the diagnosis of pathological changes in heart valves and papillary muscles [1].

Methods

The main objective of our study was to provide a comprehensive discussion of the topic of papillary muscles, considering both anatomical and clinical aspects. To achieve this, an extensive review of available literature was conducted, utilising databases such as PubMed, Google Scholar, and Scopus. The decision was made to search the aforementioned databases for publications using keywords such as papillary muscles, clinical aspects of papillary muscles, anatomical variations of papillary muscles, and papillary muscle rupture. In our publication we decide to include only the publications providing all the necessary information regarding the number of cadavers examined, and the shapes and number of papillary muscles in both left and right ventricles.

Embryonic development

The embryonic development of the papillary muscles of the left ventricle initiates between the fifth and seventh week of foetal life from the dorsal myocardium, composed of thick trabeculae present in the inner layer of the myocardium [7].

After 7 weeks, there is an elongation of the anterior and posterior parts of the dorsal trabeculae. This process continues until the 10th week of foetal life. During this period, connections between the anterior and posterior parts of the dorsal trabeculae and the ventricular wall disappear. Morphological features of the papillary muscles become apparent during this time, connecting to the myocardium only at the base

– towards the left ventricular wall – and at the apex, in the atrioventricular region, through the cushion tissue of developing mitral valve leaflets. Between the 10th and 12th weeks, the formation of chordae tendineae from the cushion tissue of the valves begins, and from the 14th week onwards, observable differences in the morphological features of papillary muscles emerge. The development of fully mature papillary muscles along with chordae tendineae continues until the 19th week of foetal life [7].

Differences in the development of papillary muscles between the left and right ventricles are minimal. They include the development of the septal papillary muscle of the right ventricle, which initially lacks a connection to the septal leaflet of the tricuspid valve. This connection is dependent on the process of delamination [8].

Histology

Papillary muscles are primarily composed of cardiac muscle tissue and connective tissue. The muscle fibres mostly exhibit a longitudinal orientation, aligning parallel to the muscle axis. In the peripheral region of papillary muscles, a circular arrangement of muscle fibres is observed. Connective tissue serves as the framework for papillary muscles, organising and separating individual groups of muscle fibres uniformly. Key areas of connective tissue concentration include the subendocardial zone, the vicinity of blood vessels, and the distal parts of the muscles, where chordae tendineae originate. In the perivascular zone, small clusters of fat cells are also present [9].

Anatomical variations

Papillary muscles are present in 2 chambers of the heart – the left and the right. Conventionally, it is accepted that within the right ventricle, a standard arrangement of papillary muscles (PM) can be observed. This arrangement consists of 3 muscles: anterior (APM), inferior (IPM), and septal (SePM) papillary muscle. However, in many cases, variations can be observed.

Similarly, within the left ventricle, the classical arrangement comprises 2 papillary muscles. These muscles include the superior (anterolateral) and the inferior (posteromedial) papillary muscle.

Papillary muscles of the right ventricle

The anatomical structure of the papillary muscles in the right ventricle, as described above, is present in most cases. However, there are numerous reports of structural differences within these structures.

While the standard arrangement includes only 3 papillary muscles, Aktas *et al.* in 2004 observed that their number can vary between 2 and 9. There may also be variations in their length, shape, and the chordae

tendineae attached to them [10]. In a study by Nigri *et al.* in 2000, on 79 hearts, the presence of APM was observed in 100% of hearts with one or two cusps. Single-cusped APM accounted for 81% of all hearts, with 51 of them coexisting with at least one septal papillary muscle (SePM), of which 43.8% (28 hearts) had only one SePM, 15.6% (10 hearts) had 2, 12.5% (8 hearts) had 3, and 7.8% (5 hearts) had 4. In the remaining 20.3% (13 hearts), no septal muscle was present. In hearts with double-cusped anterior papillary muscles (15 hearts – 19% of all hearts), 11 hearts (73.3%) exhibited at least one SePM, up to 4, while in 4 hearts (26.6%), no SePM was observed. In the same study, the length of APM varied between 5.9 and 40.03 mm, with double-cusped ones being shorter (5.19 mm to 24.45 mm) and often connected by a muscular bridge, while those with a single cusp were longer (10.44 mm to 40.03 mm). IPM was present in all hearts, with one to four heads, where most hearts (25.4%) had one and the fewest (6.3%) had 4. In 78% of cases, PPM was accompanied by at least one septal papillary muscle. The length of IPM varied between 2.00 and 30.05 mm, with single-cusped muscles having the longest average length and 4-cusped ones the shortest. SePM occurred in 62 hearts (78.5%) and had one to four heads, with a predominance (41.7%) of single-cusped ones, which also exhibited the greatest length (from 2 mm to 14.04 mm) and the shortest length in 4-cusped ones (from 2.37 mm to 5.46 mm). Although the anatomical standard is the presence of one APM, one IPM, and one SePM, in this study, it accounted for only 6.32% of cases; the most common combination was one APM, 2 IPM, and one SePM, constituting 20.2% of cases [10].

In a study by Saha *et al.* on 52 hearts, 23.07% exhibited the arrangement of one APM, one IPM, and one SePM. They also demonstrated the presence of 3-cusped APM, which, however, constituted a significant minority (5.76%) compared to the 78.84% of single-cusped ones. In every heart, there was an anterior papillary muscle, but in 8 hearts, or 15.38%, no IPM was observed. SePM was absent in 55.76% of cases. They also demonstrated the presence of accessory muscles in various locations. Double muscles were mainly connected on the anterior wall (62.50%), while on the posterior wall (64.28%) and septum (100%), they were separate and arranged in parallel. Triple muscles occurred primarily in the posterior wall (80%), with 2 connected separately, mainly in the anterior (66.66%). The standard shape of papillary muscle cusps is conical, but in this study, various shapes were observed: flat, bifurcated, tricuspid, and trunk-like. Conical shape was observed in the majority of SePM (90.62%), but only in 12.12% of APM and 2.94% of IPM. In these latter 2 groups, mainly flat muscles were present (51.51% of APM and 88.23% of IPM), while only 9.37% of SePM had this shape. Bifurcated and trunk-like structures were presented only by anterior and inferior papillary muscles, and

tricuspid ones only by the APM (7.57%). Chordae tendineae emerge from the apex of each papillary muscle, with their number varying depending on the muscle – in anterior ones from 2 to 20, posterior ones from 2 to 14, and septal ones from 1 to 7. These muscles also connect to the valve leaflets – in 37.87% of hearts, SePM was attached to the anterior and posterior leaflets, constituting the most classical connection, but in the remaining individuals, it was found that SePM attached to all 3 leaflets, to the anterior and septal ones, or only to the anterior one. The IPM typically connects to the posterior and septal leaflets, but in the examined cases, it usually connected only to the posterior leaflet (45.58%) or to the anterior and posterior ones (36.56%). In 50% of cases, SePM was attached to the posterior and septal leaflets, or in 25% of cases, it exhibited the standard attachment to the anterior and septal leaflets [11].

Differences also exist in the vascularisation of the papillary muscles of the right ventricle, as shown in a study on 36 hearts conducted by Zajączkowski *et al.* [12]. The researchers utilised the classification presented by Kosiński *et al.*, which includes the course of the septomarginal trabecula in the right ventricular outflow tract and its relationship to the APM. It consists of 4 types: Type I – the trabecula does not directly connect to the APM; its structure is continuous and uniform. Type II – the trabecula is in constant contact with the APM. Type III – a persistent connection between the trabecula and the APM. Type IV – the APM divides the trabecula into 2 parts [13].

The anterior papillary muscle was vascularised by branches of the left and right coronary arteries in 28 hearts. In 8 cases, blood to this muscle was supplied only by the left coronary artery (LCA). Three hearts belonged to type I according to Kosiński [13], and each received blood from both the LCA and the right coronary artery (RCA). Four hearts were type II; 3 of them had the same vascularisation of the APM as hearts in type I, and in one the supply was only from the LCA. Type III comprised the most numerous group of hearts, i.e. 20. In 14 of them (70%), blood for the APM flowed from both the RCA and the LCA, while in the remaining 6 (30%), it came only from the LCA. In 89% of type IV hearts (8), the studied muscle was vascularised by both the LCA and RCA, while in 11% (one heart), only by the LCA. These results indicated that in type III, the total cross-sectional area of arteries branching from the LCA is larger than those branching from the RCA. The same relationship occurred in type IV [12].

Papillary muscles of left ventricle

Papillary muscles of the left ventricle, as mentioned in the introduction, are usually described as 2 papillary muscles: the superior papillary muscle (SPM) and the IPM. However, there are significant variations in

the morphology of PMs. PMs can be classified into different variants based on shape, number of heads/bellies, presence of common or separate basal segments, and type of vascularisation [14].

In a study by Saha and Roy, 52 formalin-fixed hearts were examined for the number, spatial orientation, shape, attachment sites, additional PMs, and the number of their chordae tendineae. Additionally, the length and width of PMs were measured. Both types of PMs were present in each heart. The minimum number was 2 muscles, and the maximum was 7. The classical image of 2 PMs was observed in 25% of cases. A single belly was found in 65.38% of SPMs and 28.84% of IPMs. Auxiliary bellies were found in 34.61% of PMs, and additional bellies were present in 71.15%. The maximum number of bellies, 7, was only present in 2 hearts. PMs with double bellies – varied distribution PMs with triple bellies – usually interconnected in SPM PMs with quadruple and quintuple bellies – exclusively present in IPM, SPMs were mainly wedge-shaped – 66.23% and originated from the upper and middle third of the sternocostal wall, while IPMs were mainly cone-shaped – 45.76% originating from the middle part of the diaphragmatic wall. It is noteworthy that only a few auxiliary PMs were connected to the valve leaflets. The average length and width of SPM were 2.6 cm by 0.9 cm, while for PPM, it was 2.51 cm by 0.89 cm [11].

In another study conducted by Gunnal *et al.*, PMs were described in 116 formalin-fixed hearts. The classical image of 2 PMs was observed in only 4 samples – 3.44%. Two groups of PMs were observed in 50 samples – 43.11%, 3 in 37 samples – 31.90%, and 4 in 25 – 21.55%. PMs most frequently exhibited a wide apex shape – 60 samples, and least frequently a fan-shaped shape – 15 samples. Cone and pyramid shapes appeared with intermediate frequency. In one ventricle, PMs of different shapes could be present. The location of PMs was mainly indicated in the middle third of the ventricular wall – 95% [15].

In the study of Hosapatna *et al.*, 15 human hearts were examined for the anatomy of papillary muscles. All PMs of the left ventricle had a cone-shaped appearance. In comparison to the right ventricle, double-headed PMs were more frequently observed in the left ventricle. Double IPMs were observed more frequently – 6 samples, than double SPMs – 2 samples. It was demonstrated that PMs of the left ventricle are longer than those of the right ventricle [16].

A study from 2022 by Hosapatna *et al.* included the analysis of the structure of PMs in 10 hearts. Three shapes of classical PM apices were observed – cone-shaped, truncated, and flat, as well as 3 types of chordae tendineae branching – single (unbranched), fan-shaped (branched), and reticular (irregular), with the reticular pattern being the rarest. The SPM of the left ventricle presented a single cone-shaped head in 4 hearts, bifurcated in 3, trident-shaped in

2 hearts, and flat in one. On the other hand, the IPM was trident-shaped in 5 hearts, bifurcated in 4, and single cone-shaped in one. In all cases, PMs originated from the lower 1/3 of the ventricular wall. Additional PMs were observed in 3 hearts [17].

Bhadoria *et al.* examined 50 hearts for the morphology of PMs. All hearts were equipped with 2 PMs of the left ventricle. Sixteen (32%) hearts had a wide apex, 15 (30%) had a pyramidal shape, 10 (20%) had a fan-shaped shape, and 9 (18%) had a cone-shaped shape. The average length and width of the SPM were 16.41 mm and 7.98 mm, respectively, while for the IPM, it was 14.64 mm and 8.44 mm [18].

In 20 heart muscles, Raj *et al.* examined the variations of PMs. 21.3% of left ventricle PMs had a cone-shaped apex, 26.7% had a wide shape, and 21.3% had a pyramidal shape. Classic papillary muscles with one belly were present in 59.3%, with 2 and 3 bellies in 30% and 3.3%, respectively, while multi-apex PMs of the left ventricle were present in 12.7%. The length of the left ventricle SPM was 2.15 cm, and IPM was 1.78 cm [19].

Kavitha *et al.* examined 100 formalin-fixed human hearts. The SPM originated from the anterolateral wall in 82% of cases, while in the remaining 18%, it was observed on the diaphragmatic wall of the ventricle. Its average length was 18.8 mm, and the average width was 6.89 mm. On the other hand, the IPM originated from the diaphragmatic wall of the left ventricle in 90% of cases and from the area of the sternocostal wall in 10%. The average length and width of the IPM were 18.89 mm and 6.25 mm, respectively [20].

In another study, Radhakrishnan *et al.* from Stanley Medical College in Chennai conducted a PM study involving 100 hearts. It was shown that the most common attachment of the SPM was on the mid-third of the left ventricular wall (74%), and less frequently on the upper third (16%) and the lower third (10%). Similarly, IPM was most commonly located on the mid-third of the wall (81%), with occurrences on the upper and lower thirds of the left ventricular wall at 13% and 6%, respectively. SPM of the left ventricle typically had one belly in 71% of cases, 2 bellies in 18%, 3 in 9%, 4 in 1%, and 5 in 1%. For IPM, one belly was present in 48% of cases, 2 in 39%, 3 in 8%, 4 in 4%, and 5 in 1% of the examined left ventricle PMs. Differences were also observed in the number of chordae tendineae attachments to PMs. SPM had an average of 8 chordae tendineae, and IPM had an average of 6 [21].

The vascular supply of the left ventricular papillary muscles can vary between cases. In a study involving 20 examined hearts, it was observed that the superior papillary muscle (SPM) was commonly supplied by the left circumflex artery: In 11 cases, the blood supply to the SPM originated from the left marginal artery. In 7 hearts, it was supplied by the second diagonal branch. In the remaining 2 cases, the supply came from the left anterior descending artery (LAD).

On the other hand, the inferior papillary muscle (IPM) in 14 hearts was vascularised by the right coronary artery, while in 6 hearts, it received its blood supply from the left coronary artery: In 6 cases, the blood supply to the IPM came from the posterior interventricular branch. In 8 cases, it was supplied by the first left posterior ventricular branch. In 5 cases, it received its supply from the left marginal artery. In 1 case, the IPM was supplied by the left posterior ventricular branch of the circumflex artery [22].

In another study, the blood supply to the SPM originated from the descending branch of the anterior descending artery or diagonal branches of the coronary arteries or the end of the left marginal artery. The IPM was supplied by the left circumflex artery and/or branches of the right coronary artery [23].

Literature describes instances of a single papillary muscle (SPM) in the left ventricle. This is typically the superior papillary muscle, constituting 65% of variants, with the posterior SPM being rarer. The SPM is shifted towards the centre and gives off chordae tendineae to both the anterior and posterior leaflets of the mitral valve, forming a so-called parachute mitral valve. The occurrence of SPM may be associated with a significant hypoplasia of one of the muscles [24, 25].

Shapes and their corresponding quantities of various papillary muscles in the left and right ventricles, as presented in the above-mentioned studies [11, 15–18], are summarised and illustrated in Table 1. The number of muscles may vary from the number of hearts in the studies due to the possibility of multiple shapes of papillary muscles in one heart. Anatomical variations in the shapes of the papillary muscles are shown in Figure 1.

Clinical aspects of left ventricular papillary muscles

Papillary muscles are not only important morphologically in the structure of the heart, but they also play a crucial role in the functioning of the cardiac muscle, responsible for pumping blood into the body's blood vessels. Dysfunctions in the operation of papillary muscles can lead to a spectrum of different symptoms with varying degrees of severity. Clinical manifestations include symptoms of mitral valve insufficiency, ranging from mild, presenting as a transient systolic murmur, to severe cases where pulmonary oedema may occur [26].

Rupture of papillary muscles – the cause of acute mitral regurgitation (AMR)

Rupture of the left ventricular papillary muscles (papillary muscle rupture – PMR) is a relatively rare complication of myocardial infarction (MI) and occurs at a frequency of about 0.26% [27]. Despite this, along with other mechanical complications of MI, this condition accounts for up to 18% of all deaths in patients

hospitalised due to a heart attack [7]. Understanding the frequency of occurrence of individual anatomical variants, both papillary muscles themselves and their connections to the individual leaflets of the mitral valve, as well as variations in blood supply, allows for predicting the risk of PMR as an early complication of MI. This is particularly important for implementing meticulous observation in patients with anatomical variations that predispose them to PMR. This is crucial due to the development of acute mitral regurgitation (AMR) in the course of PMR. Acute mitral regurgitation is a life-threatening condition manifested by sudden pulmonary oedema, hypotension, and heart failure, even progressing to cardiogenic shock. Therefore, rapid diagnosis and the initiation of effective pharmacological treatment are essential, ultimately leading to cardiac surgery involving the repair or replacement of the mitral valve complex [28].

Among the papillary muscles of the left ventricle, the inferior papillary muscle is particularly vulnerable to acute ischaemia and, consequently, rupture. This is directly related to its single blood supply from the posterior descending artery (PDA) [29]. In contrast, the superior papillary muscle has double blood supply – vessels branching from the left anterior descending artery (LAD) and the left circumflex artery (LCx). Consequently, it is less prone to rupture caused by ischaemia [28, 30]. This is the most prevalent variant of blood supply. Other variants primarily involve differences in the PDA, which can originate from either the RCA, making it a dominant coronary artery (80% of cases), or the LCA in about 20% of cases [31]. In this case, anatomical variants involving the presence of additional papillary muscles in the left ventricle seem to be advantageous and to some extent protect against AMR.

The frequency of PMR occurrence depends on factors such as gender, age, substance abuse, or the region of the heart wall that has suffered ischaemia [28]. The time elapsed from the onset of ischaemia to effective reperfusion also remains significant [32].

Significance of the anatomical variations of papillary muscles in electrophysiology and cardiac surgery

Understanding the anatomical variations of papillary muscles and the entire mitral valve complex, including valve leaflets, chordae tendineae, papillary muscles, and the mitral annulus, is crucial for invasive cardiologists, cardiac surgeons, and electrophysiologists to optimally perform procedures on the mitral valve and papillary muscles. One such procedure used to treat various arrhythmias is radiofrequency ablation (RFA). It is observed that foci of ventricular arrhythmias are sometimes located within the papillary muscles or other parts of the valvular apparatus. Arrhythmias originating from papillary muscles often

Table 1. The shape and number of papillary muscles in the right and the left ventricle of the heart

Variable	Papillary muscle (PM)	Shape	Number
Papillary muscles of the right ventricle	Anterior papillary muscle (APM)	Conical	41
		Flat topped	3
		Truncated	2
		Pyramidal	17
		Fan shape	9
		Broad apex	3
	Inferior papillary muscle (IPM)	Conical	37
		Flat topped	2
		Truncated	1
		Bifurcated	1
		Bifid base and fuse apex	2
		Pyramidal	10
		Fan shape	12
		Broad apex	10
	Septal papillary muscle (SePM)	Conical	67
		Flat topped	2
		Truncated	1
		Bifurcated	1
Papillary muscles of the left ventricle	Superior papillary muscle (SPM)	Conical	87
		Flat-topped	11
		Truncated	51
		Bifurcated	11
		Trifurcated	5
		Broad-apexed	76
		Pyramidal	46
		Fan-shaped	25
		Flat-topped	1
		Conical	137
	Inferior papillary muscle (IPM)	Flat-topped	9
		Truncated	27
		Bifurcated	26
		Trifurcated	11
		Broad-apexed	73
		Pyramidal	37
		Fan-shaped	34

manifest as benign disturbances such as premature ventricular contractions; however, in specific cases, they can serve as a starting point for dangerous ventricular arrhythmias, such as ventricular fibrillation [33]. In such situations, ablation becomes necessary, raising questions about the safety and impact of this

procedure on the function of papillary muscles and the mitral valve, particularly concerning the development of mitral regurgitation (MR) or other valvular dysfunctions [34].

In light of emerging reports on potential complications after RFA within papillary muscles and the val-

vular apparatus (worsening or occurrence of mitral regurgitation), attempts are being made to investigate the influence of radiofrequency ablation on the functioning of the valvular apparatus [35, 36].

Studies conducted by Edward *et al.* on a group of 65 patients with ventricular arrhythmia foci (premature ventricular contraction/ventricular tachycardia) located within the right (5 patients) and left (60 patients) ventricular papillary muscles did not find statistically significant deterioration in the function of the valvular apparatus after RFA [34]. Moreover, in some cases, the degree of atrioventricular valve regurgitation assessed by transthoracic echocardiography (TTE) decreased. However, this applied to too small a percentage of patients to draw definitive conclusions. An inherent limitation in assessing the extent of damage to the structure and function of the left ventricular papillary muscles after RFA is that both mitral valve leaflets are connected by chordae tendineae to both the superior and inferior papillary muscles. Thus, significant damage to a single papillary muscle during ablation may not be reflected in imaging results, such as TTE evaluating the degree of mitral regurgitation [37]. In the presented group, the majority of ablations (38 out of 60 performed on the left ventricular papillary muscles) targeted the inferior papillary muscle, reflecting the fact that arrhythmia foci more often localise within this muscle [34].

Congenital heart defects associated with papillary muscles

Papillary muscle abnormalities can significantly impair the haemodynamic performance of the heart. Parachute mitral valve, parachute-like mitral valve, and Shone's anomaly are among the most common papillary muscle-related abnormalities found in the population. The parachute mitral valve, associated with a single left ventricular papillary muscle, may be one of the most common causes of isolated mitral stenosis in the infants [38]. Cardiac abnormalities co-occurring with the parachute mitral valve include coarctation of the aorta, subvalvular aortic stenosis, and supra-valvular mitral annulus. Complex of these 4 abnormalities is referred to as Shone's anomaly. The clinical manifestation of Shone syndrome includes a systolic murmur, dyspnoea, and increased exercise intolerance [39]. In diagnosis, echocardiography is used to visualise abnormalities in the heart, indicating the basis of the above-mentioned symptoms. However, Shone syndrome does not always manifest with all 4 defects. In some cases, one of the defects is absent or other defects such as quadricuspid aortic valve, persistent ductus arteriosus, or ventricular septal defects are present [40].

Neoplasms involving papillary muscles

Among the tumours involving the papillary muscles, the most common are metastases, but there are also primary lesions of a benign or malignant nature.

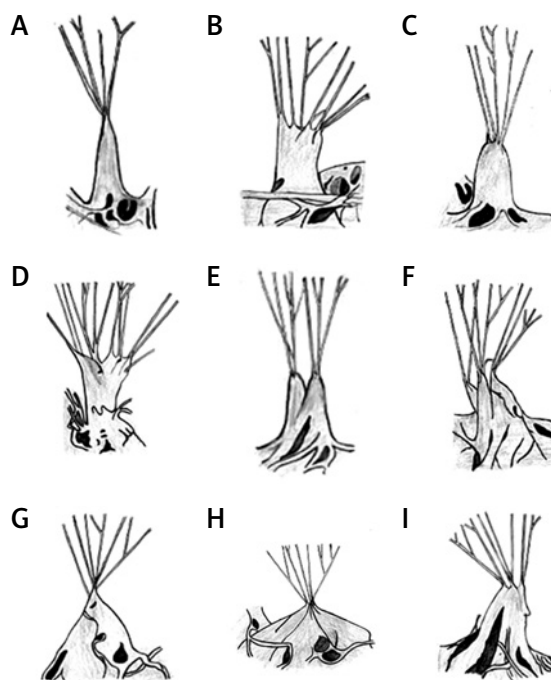


Figure 1. Variations in the shape of papillary muscles: A – conical; B – flat-topped; C – truncated; D – broad-apexed; E – bifurcated; F – trifurcated; G – pyramidal; H – fan-shaped; I – bifid base and fuse apex. Bifid base and fuse apex shape occurred only in the right ventricle

The most common sources of metastasis include lung cancer, breast cancer, and malignant melanoma. Primary benign tumours include myxoma (most common), fibroelastoma, and rhabdomyoma that may involve the papillary muscles. Sarcoma is the most common primary malignancy developing within the heart. Myocardial involvement by the neoplastic process can manifest as left ventricular outflow tract stenosis, decreased ejection fraction, or arrhythmias. In the diagnosis, cardiac magnetic resonance is used to detect and determine the nature of the lesion [41].

Clinical aspects of right ventricular papillary muscles

The anatomical variations of right ventricular papillary muscles also hold clinical significance. Certain variants may directly cause or predispose individuals to specific conditions, while others appear to have a protective influence on the functioning of the valvular apparatus and, consequently, cardiac muscle performance.

Anatomic anomalies of right ventricular papillary muscles as a cause of pulmonary embolism

An excessively developed complex of papillary muscles may be a potential cause of chronic pulmonary embolism. Ker described a case of a patient ex-

periencing recurrent episodes of pulmonary embolism, with the probable cause being an overgrown complex of papillary muscles located in the upper part of the right ventricular lateral wall. Such a rare variant may lead to the formation of clots in the right ventricle, potentially through 2 mechanisms: 1) Due to turbulence in blood flow within the right ventricle. 2) Due to the predisposition of this variant to generate ventricular arrhythmias, which increase the risk of blood clotting within the right cardiac chamber.

This is an important clinical aspect requiring further investigation [42].

Arrhythmias emerging from right ventricular papillary muscles

The anterior papillary muscle can, in certain situations, be a focus for the occurrence of ventricular arrhythmias. In a study conducted by Lazzari *et al.*, the nature of additional contractions originating from the anterior papillary muscle was assessed using Holter ECG monitoring. It was demonstrated that the anterior papillary muscle can be a source of premature ventricular contractions (PVCs) occurring at an average frequency of 9.9 per minute and, less frequently, ventricular tachycardia (VT). Most patients did not experience any symptoms of irregular heartbeats, except for palpitations in a few cases. Based on the results, arrhythmias from the anterior papillary muscle can occur in people with entirely normal heart structure and are not associated with an increased risk of death [43].

Variants of papillary muscles associated with increased risk of sudden cardiac death

Sudden cardiac death is an unexpected, sudden death due to cardiac reasons, occurring within an hour from the onset of the first symptoms. It is one of the leading causes of death in developed countries [44]. Aktas *et al.* observed that individuals whose cause of death was sudden cardiac death often had a variant of the anterior papillary muscle with a single head. Additionally, the authors noted a significant prevalence of variants of the inferior papillary muscle with flattened (flat top) and conical heads in this group of patients [45].

Favourable impact of certain variants on tricuspid regurgitation

The apex of the papillary muscle is the part least supplied with blood, and it significantly exhibits insufficient oxygen and nutrient supply. Therefore, this part of the papillary muscle is most susceptible to ischaemia, even in the case of the closure of small arterial vessels by a clot, the closure of which does not cause symptoms of a heart attack. If the rupture of one of the heads of the papillary muscle occurs due

to such ischaemia, tricuspid regurgitation symptoms may appear. Studies show that the rupture of a single head of the papillary muscle yields effects similar to the situation in which one of the large chordae tendineae ruptures. Therefore, patients with additional heads of the papillary muscle are less prone to such ischaemic complications, which appears beneficial [11].

Conclusions

Papillary muscles are anatomical structures characterised by considerable variability in their number, shape, location, and vascularisation. A number of pathologies in the functioning of the myocardium can be explained by specific variants of the papillary muscles. Knowledge of anatomy remains a prerequisite for the proper performance of surgical procedures within the valvular apparatus of the heart, hence a better understanding of the structure and function of the papillary muscle complex is of considerable importance. Noteworthy is the possibility of using modern imaging methods such as cardiac magnetic resonance and echocardiography. This is particularly important in paediatric cardiology, where papillary muscle pathologies translate into specific clinical conditions such as mitral stenosis in the case of a parachute valve associated with a single left ventricular papillary muscle. The dynamic development of invasive cardiology and the introduction of new treatment methods such as radiofrequency ablation and transcatheter valve replacement create the need for continuous evaluation of the impact of these procedures on the functioning of anatomical structures of the heart, including the papillary muscles. The papillary muscles remain an important field for further anatomical and clinical research in identifying variants that predispose to or cause specific clinical conditions.

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Conflict of interest

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References

1. Chen S, Sari CR, Gao H, Lei Y, Segers P, De Beule M, Wang G, Ma X. Mechanical and morphometric study of mitral valve chordae tendineae and related papillary muscle. *J Mech Behav Biomed Mater*. 2020; 111: 104011.

2. Xanthos T, Dalivigkas I, Ekmektzoglu K. Anatomic variations of cardiac valves and papillary muscles of the right heart. *Ital J Anat Embryol.* 2011; 116(2): 111-126.
3. Zalewski J, Nessler J. Niedomykalność zastawki mitralnej. Część I. Mechanizmy i etiologia. *Kardiologia Inwazyjna.* 2016; 11(1): 21-24.
4. Ramsheyi SA, Pargaonkar S, Lassau JP, Acar C. Morphologic classification of the mitral papillary muscles. *J Heart Valve Dis.* 1996; 5(5): 472-476.
5. Rodriguez F, Langer F, Harrington KB, Tibayan FA, Zasio MK, Liang D, Daughters GT, Ingels NB, Miller DC. Effect of cutting second-order chordae on in-vivo anterior mitral leaflet compound curvature. *J Heart Valve Dis.* 2005; 14(5): 592-601.
6. Rodríguez F, Langer F, Harrington KB, Tibayan FA, Zasio MK, Cheng A, Liang D, Daughters GT, Covell JW, Criscione JC, Ingels NB, Miller DC. Importance of mitral valve second-order chordae for left ventricular geometry, wall thickening mechanics, and global systolic function. *Circulation.* 2004; 110(11 Suppl 1): 115-122.
7. Oosthoek PW, Wenink AC, Wisse LJ, Gittenberger-de Groot AC. Development of the papillary muscles of the mitral valve: morphogenetic background of parachute-like asymmetric mitral valves and other mitral valve anomalies. *J Thorac Cardiovasc Surg.* 1998; 116(1): 36-46.
8. Lamers WH, Virágh S, Wessels A, Moorman AF, Anderson RH. Formation of the tricuspid valve in the human heart. *Circulation.* 1995; 91(1): 111-121.
9. Kuta W, Kosiński A, Kozłowski D, Nowicka E, Grzybiak M. Histological remarks regarding the structure of the septal papillary muscles in the hearts of elderly people. *Geriatrics.* 2012; 6(4): 207-211.
10. Nigri GR, Di Dio LJ, Baptista CA. Papillary muscles and tendinous cords of the right ventricle of the human heart: morphological characteristics. *Surg Radiol Anat.* 2001; 23(1): 45-49.
11. Saha A, Roy S. Papillary muscles of left ventricle-Morphological variations and its clinical relevance. *Indian Heart J.* 2018; 70(6): 894-900.
12. Zajączkowski MA, Gajić A, Kaczyńska A, Zajączkowski S, Kobiela J, Kamiński R, Kosiński A. Individual variability of vascularization of the anterior papillary muscle within the right ventricle of human heart. *PLoS One.* 2018; 13(10): e0205786.
13. Kosiński A, Nowiński J, Kozłowski D, Piwko G, Kuta W, Grzybiak M. The crista supraventricularis in the human heart and its role in the morphogenesis of the septomarginal trabecula. *Ann Anat.* 2007; 189: 447-456.
14. Berdajs D, Lajos P, Turina MI. A new classification of the mitral papillary muscle. *Med Sci Monit.* 2005; 11(1): BR 18-21.
15. Gunnal SA, Wabale RN, Farooqui MS. Morphological variations of papillary muscles in the mitral valve complex in human cadaveric hearts. *Singapore Med J.* 2013; 54(1): 44-48.
16. Hosapatna M, Souza A, Das M, Supriya S, Ankolekar V, Souza AS. Morphology of papillary muscles in human adults: a cadaveric study. *Ibnosina J Med BS.* 2014; 6(4): 168-172.
17. Hosapatna M, DSouza A, Ankolekar VH. Morphology of the papillary muscles and the chordae tendineae of the ventricles of adult human hearts. *Cardiovasc Pathol.* 2022; 56: 107383.
18. Bhadoria P, Bisht K, Singh B, Tiwari V. Cadaveric study on the morphology and morphometry of heart papillary muscles. *Cureus.* 2022; 14(2): e22722.
19. Raj P, Pallavi, Singh AK. Adult human cadaveric heart assessment for anatomical variations of papillary muscles in both the ventricles. *IJTPR* 2022; 12(6): 143-148.
20. Kavitha S, Shastri D, Shanthi KC. Morphometric analysis of papillary muscles in both ventricles of hearts. *IOSR J Dental Med Sci* 2018; 17(3): 26-33.
21. Radhakrishnan NS. Variations in the number and attachment of papillary muscles. *Diss. Stanley Medical College, Chennai,* 2009.
22. Rusu MC, Petrescu CI, Niculescu V, Ionescu N, Vlad M. Considerations on the left papillary muscles microangiography. *Rom J Morphol Embryol.* 2006; 47(1): 63-66.
23. Ranganathan N, Burch GE. Gross morphology and arterial supply of the papillary muscles of the left ventricle of man. *Am Heart J.* 1969; 77(4): 506-516.
24. Yuan SM. Parachute mitral valve: Morphology and surgical management. *Turk Gogus Kalp Damar Cerrahisi Derg.* 2020; 28(1): 219-226.
25. Marino BS, Kruger LE, Cho CJ, Tomlinson RS, Shera D, Weinberg PM, Gaynor JW, Rychik J. Parachute mitral valve: morphologic descriptors, associated lesions, and outcomes after biventricular repair. *J Thorac Cardiovasc Surg.* 2009; 137(2): 385-393.
26. De Busk RF, Harrison DC. The clinical spectrum of papillary-muscle disease. *N Engl J Med.* 1969; 281: 1458-1467.
27. Hawranek M, Gąsior M, Nożyński J, Poloński L. Przyczyny zgonów chorych z zawałem serca w dobie leczenia reperfuzyjnego. *Folia Cardiol.* 2004; 11(4): 239-245.
28. Singam NSV, Ghafghazi S. Papillary muscle rupture after acute inferior myocardial infarction. *Tex Heart Inst J.* 2021; 48(4): e186717.
29. Chevalier P, Burri H, Fahrat F, Cucherat M, Jegaden O, Obadia JF, Kirkorian G, Touboul P. Perioperative outcome and long-term survival of surgery for acute post-infarction mitral regurgitation. *Eur J Cardiothorac Surg.* 2004; 26(2): 330-335.
30. Machura M, Hudzik B, Gąsior M. Mechaniczne powikłania zawału serca. *Folia Cardiol.* 2017; 12(6): 565-569.
31. Estes EH Jr, Dalton FM, Entman ML, Dixon HB 2nd, Hackel DB. The anatomy and blood supply of the papillary muscles of the left ventricle. *Am Heart J.* 1966; 71(3): 356-362.
32. Figueras J, Calvo F, Cortadellas J, Soler-Soler J. Comparison of patients with and without papillary muscle rupture during acute myocardial infarction. *Am J Cardiol.* 1997; 80(5): 625-627.
33. Naksuk N, Kapa S, Asirvatham SJ. Spectrum of ventricular arrhythmias arising from papillary muscle in the structurally normal heart. *Card Electrophysiol Clin.* 2016; 8(3): 555-565.
34. Edward JA, Zipse MM, Tompkins C, Varosy PD, Sandhu A, Rosenberg M, Aleong R, Tzou WS, Borne RT, Sauer WH, Nguyen DT. Follow-up after catheter ablation of papillary muscles and valve cusps. *JACC Clin Electrophysiol.* 2019; 5(10): 1185-1196.
35. Piccione W, Goldin M. Mitral valve dysfunction following papillary muscles cryoablation. *Ann Thorac Surg.* 1988; 46(3): 347-348.
36. Mochizuki A, Nagahara D, Takahashi H, Saito R, Fujito T, Miura T. Worsening of mitral valve regurgitation after

- radiofrequency catheter ablation of ventricular arrhythmia originating from a left ventricular papillary muscle. *HeartRhythm Case Rep.* 2017; 3(4): 215-218.
37. Pothineni NVK, Santangeli P. Mitral valve regurgitation after papillary muscle ablation: a nonissue? *J Cardiovasc Electrophysiol.* 2021; 32(7): 1937-1938.
 38. Davachi F, Moller JH, Edwards JE. Diseases of the mitral valve in infancy. An anatomic analysis of 55 cases. *Circulation.* 1971; 43(4): 565-579.
 39. Sinfield S, Ranasinghe S, Wang S, Mendoza F, Khoynzhad A. Shone's complex and aortic dissection: case report and review of a rare, underdiagnosed congenital heart disease. *J Cardiothorac Surg.* 2022; 17(1): 21.
 40. Chandra S, Kharwar RB, Mundhekar A. Shone complex. *J Cardiovasc Ultrasound.* 2015; 23(1): 54-55.
 41. Rajiah P, Fulton NL, Bolen M. Magnetic resonance imaging of the papillary muscles of the left ventricle: normal anatomy, variants, and abnormalities. *Insights Imaging.* 2019; 10(1): 83.
 42. Ker J. Right ventricular variants and pulmonary embolism-association or coincidence? *Clin Med Insights Cardiol.* 2010; 21(4): 53-57.
 43. Lazzari JO, Fachinat A, Tambussi A. Clinical assessment of the right ventricle anterior papillary muscle extrasystoles with Holter recordings. *Pacing Clin Electrophysiol.* 1990; 13(3): 275-284.
 44. Kumar A, Avishay DM, Jones CR, Shaikh JD, Kaur R, Al-jadah M, Kichloo A, Shiwalkar N, Keshavamurthy S. Sudden cardiac death: epidemiology, pathogenesis and management. *Rev Cardiovasc Med.* 2021; 22(1): 147-158.
 45. Aktas EO, Govsa F, Kocak A, Boydak B, Yavuz IC. Variations in the papillary muscles of normal tricuspid valve and their clinical relevance in medicolegal autopsies. *Saudi Med J.* 2004; 25(9): 1176-1185.

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