

REVISITING THE RIGHT ATRIAL PECTINATE MUSCLES: ANATOMICAL VARIABILITY AND A SIMPLIFIED MORPHOLOGICAL CLASSIFICATION

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KEYWORDS

Right atrium;
Pectinate muscles;
Crista terminalis;
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SUMMARY

Purpose. — To describe the morphological variability of the pectinate muscles (PM) and crista terminalis (CT) in the right atrium, to evaluate the presence of a taenia sagittalis (TS), and to propose a simplified anatomical classification.

Methods. — Forty-five adult human hearts without major macroscopic abnormalities were dissected following a standardized protocol exposing the CT and PM. Each specimen was documented with high-resolution photographs and independently analyzed by two cardiac surgeons. The orientation of muscular fibers, the presence and number of TS, and the degree of cross-over between bundles were recorded.

Results. — The CT was identified in all specimens. Three morphological patterns of PM organization were distinguished: type I (parallel fibers without TS), type II (parallel fibers with one or more TS), and type III (disorganized fibers with multiple cross-overs). Their respective frequencies were 33.3%, 46.7%, and 20.0%. A single TS was the most frequent configuration.

Conclusions. — The PM of the right atrium show marked anatomical variability. The proposed three-type classification provides a simplified and reproducible framework for describing their organization. Beyond anatomical description, it may offer practical relevance for imaging interpretation, electrophysiological procedures, and open cardiac surgery, while providing a basis for future studies exploring the relationship between right atrial architecture and atrial arrhythmogenesis

Introduction

Definitions

The pectinate muscles (PM) of the right atrium (RA) are essential structural elements that contribute to atrial contractility and electrical conduction between the sinoatrial and atrioventricular nodes [1,2]. Predominantly located within the right atrial appendage, PM form muscular ridges oriented perpendicularly from the crista terminalis (CT), extending toward the appendage and the tricuspid vestibule [1,2]. Their morphology exhibits substantial interindividual variability.

The CT is a fibro-muscular ridge running from the superior to the inferior vena cava along the posterolateral margin of the RA. Embryologically, it marks the junction between the smooth-walled sinus venosus and the trabeculated primitive atrium [3]. Its proximity to the sinoatrial node, its involvement in arrhythmogenic mechanisms, and its usefulness as an internal landmark explain its longstanding interest in the literature [4–6].

Historical background

PM and CT anatomy were detailed in the 19th century. Cruveilhier (1843) described vertical muscular bundles on the internal surface of the RA, issuing from the appendage and directed toward the atrioventricular junction, intersected by oblique fibers of smaller caliber that created a reticulated appearance, while the remaining RA wall was smooth [7].

Rouvière (1924) later described the right atrial appendage as a triangular structure formed by thick muscular ridges partially covering the ascending aorta, and emphasized the smooth posterior atrial wall. He identified the CT as a subtle elongated ridge whose external correspondence is the terminal sulcus between the vena caval orifices [8]. This anatomical description includes a long-debated anatomical structure known as the “intervenous tubercle” (tubercle of Lower), originally described in 1669 as a transverse ridge diverting blood flow from the SVC toward the tricuspid valve [8]. Its existence was disputed by Cruveilhier and Boyer, and ultimately refuted by Loukas et al. (2012), who failed to identify such a structure in 100 hearts, suggesting earlier descriptions may reflect confusion with the superior border of the fossa ovalis [9].

In 1972, Van Praagh introduced the term *Tinea Sagittalis* (TS), referring to a wormlike muscle that lies along the sagittal plane — the front-to-back axis of the body derived from the Latin *sagitta*, meaning “arrow”. He identified it as a potential obstacle during catheter procedures with an increased perforation risk [10]. However, given its flattened morphology, it would be more accurately described as a muscular band rather than a truly wormlike structure.

Later, Anderson (1994) precisely outlined the CT trajectory toward the fossa ovalis and inferiorly to the coronary sinus ostium, highlighting its role as the boundary between the smooth and trabeculated atrial components. Although not specifically naming the TS, his description of a prominent medial PM likely corresponds to this structure [11].

Modern classifications and clinical relevance

More elaborate classifications have been proposed by Loukas (2008) and Siddiqui (2013) based on PM arrangement, number of TS, and CT variations [12,13]. However, their complexity limits adoption in clinical settings.

The growing recognition of CT and PM involvement in supraventricular tachyarrhythmias (e.g., atrial flutter, focal atrial tachycardia) reinforces the need for a practical classification [4–6,14–16]. Consequently, a clinically usable framework must integrate rigorous anatomical precision with functional simplicity, particularly for electrophysiologists and cardiac surgeons.

Study objectives

We performed a standardized anatomical study of 45 human hearts to describe the morphological variability of RA PM, propose a simplified classification that could be applicable to anatomical and clinical practice, and qualitatively assess its reproducibility through independent dual-observer evaluation.

Methods

Sample and data collection

This monocentric study (2019—2024) included 45 human adult hearts from voluntary donors. Hearts with major macroscopic pathology, congenital abnormalities, or prior cardiac surgery were excluded. Specimens were preserved via arterial perfusion using an aqueous solution containing zinc chloride (ZnCl₂), selected for mild fixation, protein coagulation, and antimicrobial properties that slow post-mortem degradation.

Dissection and documentation technique

A standardized dissection was performed through a longitudinal incision extending from one vena cava to the other, within the sinus venosus portion of the RA, medial to the CT.

A perpendicular incision was then made toward the tricuspid vestibule. This approach provided optimal visualization of the CT, PM and TS.

High-resolution photographs with fixed-distance positioning and uniform lighting were systematically obtained and archived for comparative analysis.

Anatomical assessment

Two cardiac surgeons, one of whom is anatomist in our institution (MR), independently analyzed each specimen, focusing on PM orientation, CT-PM relationships, and presence and morphology of TS. Each observer independently assigned the specimens to one of the three proposed morphological types based on the predefined anatomical criteria. Although no formal statistical measure of inter-observer agreement was calculated, both observers classified all specimens identically, resulting in complete qualitative concordance.

Results

The CT was present in all 45 hearts. PM originated from the CT and extended perpendicularly toward the lateral RA wall and the appendage, converging toward the tricuspid vestibule. Convergence was sometimes accentuated by one or more prominent PM bands (TS).

To enable consistent description, we defined three major morphological types (Table 1, Fig. 1) based on fiber orientation, TS presence, and cross-over degree:

- type I: predominantly parallel PM, no visible TS, minimal/no cross-overs (Fig. 2);
- type II: parallel PM with one or more TS, occasional crossovers (Fig. 3);
- type III: disorganized PM pattern with pseudoconvergence and multiple cross-overs (Fig. 4).

Type II phenotype was the most prevalent in this sample (21/45; 46.7%), followed by type I (14/45; 33.3%) and type III (9/45; 20.0%).

The two observers independently assigned all specimens to the same morphological category, resulting in complete qualitative concordance for the three proposed morphological patterns.

Discussion

Prior systems [12,13] include numerous subtypes with limited clinical adoption. Our simplified three-

type classification retains essential morphological elements while improving reproducibility and usability in electrophysiology and surgery. The clinical relevance of this simplified classification can be illustrated in several key areas:

Electrophysiology

Structural complexity of PM fibers favors anisotropy and could foster reentry circuits. CT involvement in atrial flutter, focal tachycardias and potentially atrial fibrillation is well documented [4—6,14—16]. Age-associated remodeling such as fibrosis at CT-PM junctions increases arrhythmogenic risk [17—19]. Recent electrophysiological literature also supports this concept, suggesting that the complex branching and overlapping architecture of the pectinate muscles may contribute to arrhythmogenic substrates by

promoting conduction heterogeneity and wavebreak within the right atrium [20]. In parallel, the role of right atrial appendage drivers in atrial fibrillation remains incompletely understood, although emerging clinical studies increasingly suggest that this region may serve not only as a trigger site but also as a substrate for arrhythmia maintenance [21,22]. Based on our observations and current knowledge, we hypothesize that more disorganized configurations (type III), or those presenting one or more TS (type II),

may contribute to greater local conduction heterogeneity and therefore represent potential anatomical substrates for atrial arrhythmogenesis.

Imaging

A prominent CT may mimic intracavitary masses on transthoracic echocardiography; TEE may improve differential diagnosis [23].

Interventions and cardiac surgery

Understanding PM anatomical variants could reduce the risk of iatrogenic injury during surgical procedures or endocardial ablation. From our practical experience in open cardiac surgery, several anatomical features of the pectinate muscles and crista terminalis directly influence the surgical approach to the right atrium. Particular care should be taken to preserve the crista terminalis whenever possible, as its transection may disrupt preferential conduction pathways and potentially injure the sinoatrial node or compromise its arterial supply [10]. Similarly, transverse section of the pectinate muscles is preferably avoided; when feasible, the atriotomy can be performed between adjacent muscular bundles, through thinner intertrabecular areas (“parchment-like”), which may both preserve conduction integrity and facilitate a more secure closure of the right atrium [24]. In addition, during retrograde cardioplegia through the coronary sinus, the purse-string suture for cannulation is preferably placed in a mechanically stronger area — typically within a prominent taenia sagittalis or, when absent, at the convergence of several pectinate muscle bundles. Types II and particularly type III may therefore theoretically increase procedural complexity due to TS prominence and complex cross-overs.

Strengths and limitations

This study presents several strengths including a systematic methodology with standardized dissections and independent dual-observer analysis. These elements contribute to reproducible classification and enables direct comparison with existing and future literature.

However, certain limitations must be highlighted including a relatively modest sample size, the

absence of direct correlation with electrophysiological or imaging data, and a potential oversimplification of intermediate morphologies. No formal statistical measurement of inter-observer agreement (such as Cohen’s kappa coefficient) was performed. Both observers independently assigned all specimens to the same morphological category. Therefore, concordance was assessed qualitatively rather than statistically.

Perspectives

Future studies combining dissection, histology, electrophysiological data, and advanced imaging (e.g., 3D cardiac MRI) are required to validate these observations and explore possible associations between pectinate muscle morphology and atrial arrhythmogenesis. Such an integrated anatomo-electrophysiological approach could represent a particularly promising avenue of research to better understand the potential role of atrial architecture in arrhythmic substrate formation.

Conclusion

This study demonstrates significant anatomical variability right atrial PM. The proposed three-type classification offers a simplified and reproducible framework for describing their organization. Further studies integrating imaging and electrophysiological data are needed to determine its clinical implications.

Figure 1 Schematic representation of the different morphological types of pectinate muscles (PM).

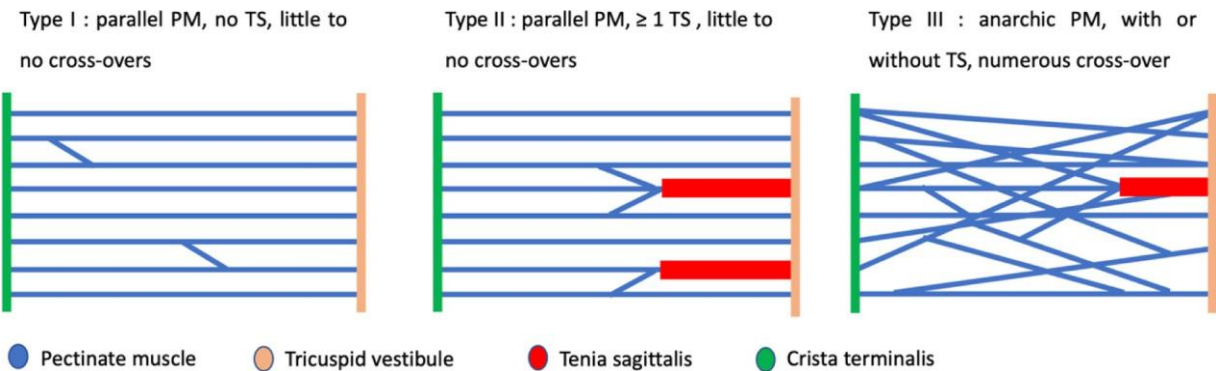


Table 1 Morphological classification of pectinate muscles (PM) of right atrium (RA).

Type	Occurrence	Morphology
Type I	14/45 = 33.3%	Parallel PM No TS Little to no cross-overs
Type II	21/45 = 46.7%	Parallel PM ≥ 1 TS Little to no cross-overs
Type III	9/45 = 20.0%	Anarchic PM With or without TS Numerous cross-overs

Figure 2 Type I — simple parallel architecture. PM present as regular, parallel ridges without notable transverse connecting structures. This represents the most orderly pattern. CT: crista terminalis; PM: pectinate muscle; TV: tricuspid vestibule.

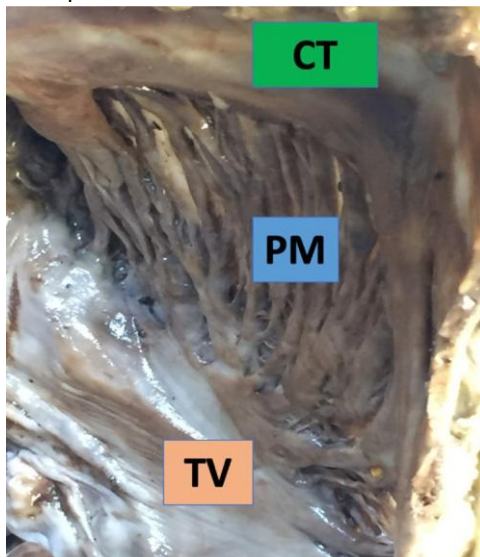


Figure 3 Type II — parallel organization with interconnections. The parallel bundles converge towards one or more tenia sagittalis (TS), forming a more complex network. Occasional cross-overs between bundles are present (arrow). PM: pectinate muscles; TS: tenia sagittalis; TV: tricuspid vestibule.

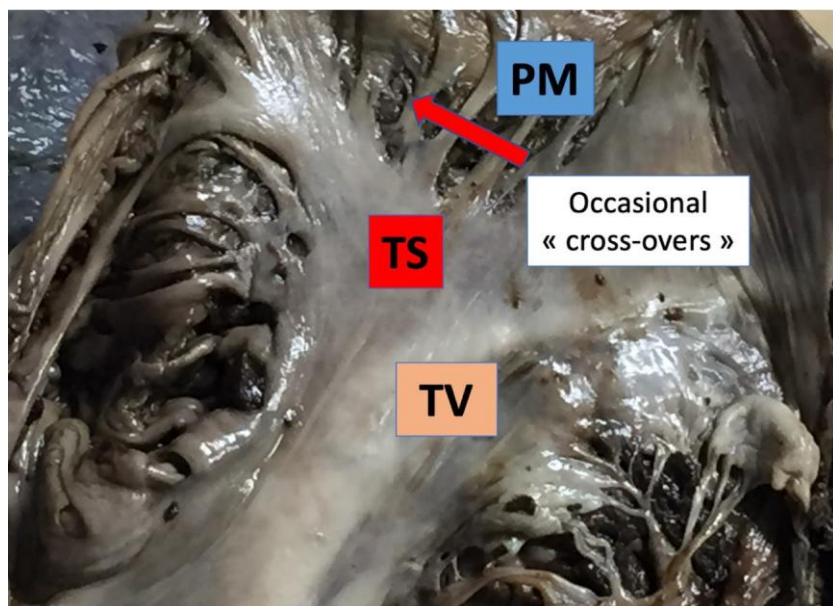
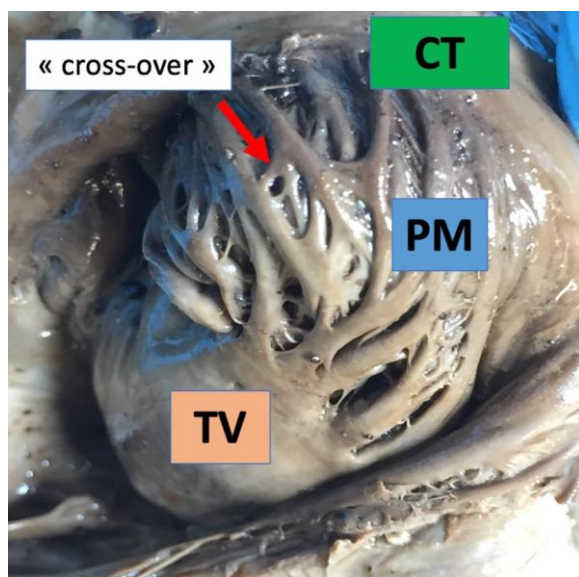


Figure 4 Type III — complex and disorganized architecture. The pectinate muscles form a tangled network with multiple cross-overs and an illusion of convergence (pseudo-convergence), creating an anarchic pattern. CT: crista terminalis; PM: pectinate muscle; TV: tricuspid vestibule.



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Ethics approval

All anatomical specimens were obtained from voluntary body donors who had provided informed consent for research and educational use. The study complies with institutional and national ethical regulations for the use of human cadaveric material. Formal ethics committee approval was not required for anatomical studies of donated bodies according to local regulations.

Consent to participate

Not applicable (study conducted on donated cadaveric material).

Consent for publication

Not applicable.

Availability of data and materials

All data generated or analyzed during this study are available from the corresponding author upon reasonable request. **Code availability**

Not applicable.

Authors' contributions

S. Madani: conceptualization, dissections, data collection, manuscript drafting.

V. Defaweux: anatomical analysis, figure preparation, manuscript revision.

A. Lagier: anatomical analysis, manuscript revision.

V. Tchana-Sato: cardiac surgical analysis, interpretation, manuscript editing.

M.A. Radermecker: conceptualization, dissections, supervision, photographic realizations, anatomical validation and analysis, critical revision, manuscript revision, final approval.

All authors read and approved the final manuscript.

Disclosure of interest

The authors declare that they have no competing interest.

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