

Heart Rhythm

What is “special” about Bachmann’s bundle?

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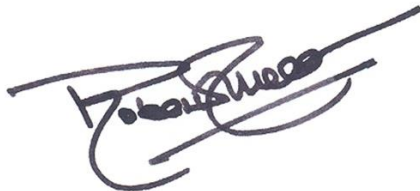
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More than a century ago, Bachmann showed that, by crushing the interatrial band, it was possible to delay interatrial conduction by a factor of four.¹ Those now seeking to identify the most appropriate means of achieving atrial resynchronization rightly place great emphasis on this key investigation. Those hoping to synchronize the atrial chambers aim to emulate the well-established advantages of ventricular resynchronization. When pacing the ventricles, the importance of the specialized atrioventricular conduction system is now fully accepted. It is, perhaps, therefore, not surprising that some of those promoting the significance of Bachmann's bundle should consider it to be part of an "atrial cardiac conduction system".² In making such a bold statement, it would seem that authors are unaware that they are opening Pandora's box, since they make no mention of the controversies that, for the past 50 years, have surrounded the comparable topic of "specialised internodal tracts".³ It is then noteworthy that the authors offer no direct histological evidence to substantiate their claim for a "conduction system" within the atrial walls of the swine heart. It seems also that they failed to take note of Bachmann's final sentence, in which he stated that his band "has not the same importance as a conducting medium as the auriculoventricular bundle for while, in the latter, crushing leads to a complete block, in the former, the same injury causes only a prolongation in the time of conduction". In this regard, Bachmann had made multiple references to an earlier study, in which attention had been focused on "the straight course taken by the fibres of this muscle band".⁴ In this study, Lewis, Meakins, and White had noted that, in certain parts of the atrial walls, there was an enhanced speed of conduction. This they again attributed to "the straight courses which the muscle fibres pursue to these regions".⁴ Over a century ago, they had needed to counter the suggestion that there was something "special" about certain parts of the atrial walls in terms of their ability to conduct. This was because, in an earlier study, Eyster and Meek had already suggested that rapidly conducting pathways might be present between the sinus and atrioventricular nodes.⁵ This suggestion was hotly disputed by Lewis, Meakins, and White.⁴ When describing their findings in the swine heart, the group of Minneapolis seemingly have no such reservations regarding the presence of the "atrial cardiac conduction system".² An example of comparable confidence is found in the study of James, when he resuscitated the notion of specialized internodal tracts in the 1960's.⁶ Careful reading of James' study shows that he considered the presence of such tracts already to have been proven. He considered his task to be no more than to demonstrate their location. As has subsequently become evident, the pathways identified by James, at least when assessed using standard histological techniques,

are made up of working atrial cardiomyocytes.³ In the light of this knowledge, it is more surprising to discover that two of the authors of the investigation of the swine heart have also contributed to a clinical study in which the controversy regarding "specialization" of the pathways is both recognized and discussed. This important study has, as its major thrust, the ability now to identify the optimal site for pacing Bachmann's bundle to achieve resynchronization.⁷ In this second study, the authors from Minneapolis have provided the anatomical and hemodynamic background to underpin the clinical findings of the group working in Vermont.⁷ The Vermont investigators had already published a "hands on" guide to pacing Bachmann's bundle.⁸ In that earlier work, anatomical correlation had been provided by one of the authors of this commentary. In that study,⁸ we find the appropriate statement that "the atria lack a well-circumscribed and distinct conduction system akin to the His-Purkinje system". We might be justified to presume, therefore, that in their two latest publications the combined investigations of the groups working in Vermont and Minneapolis have provided the evidence which substantiates the existence of the "atrial cardiac conduction system". It is hard for us, however, to find the required evidence within the works now published together in the Journal.^{2,7}

This is not to deny the existence of the interatrial band as the major pathway for conduction of the sinus impulse to the walls of the left atrium. That, of course, was the premise established by Bachmann in 1916.¹ Nor do we wish to deny the need to identify the most appropriate site to pace the pathway. The advantages of pacing the bundle as opposed to the right atrial appendage are emphasized in yet another publication in the current issue of the Journal.⁹ By using histological sections and dissections prepared by one of us, the investigators from Vermont had already shown the location and structure of Bachmann's bundle.⁸ As had also been emphasized by Saremi and colleagues,¹⁰ the bundle is a direct continuation of the terminal crest, or crista terminalis. This prominent muscular entity provides the boundary between the systemic venous sinus of the right atrium and its extensive appendage. Passing anteriorly to the orifice of the superior caval vein as the precaval band, the crest merges with the myocardium of the anterior interatrial groove, continuing as the bundle identified by Bachmann into the roof of the left atrium (Figure 1, panel A). As was noted by Lewis, Meakins, and White,⁴ the working atrial cardiomyocytes that make up the atrial walls are aggregated together in parallel fashion within the crest, as they are in the precaval band, and Bachmann's bundle. This is well seen when histological sections are assessed at increased magnification. It then becomes an easy matter to distinguish between the aggregated working cardiomyocytes making up the bundle and the specialized cardiomyocytes of the sinus node (Figure 1, panel B). Significantly,

the arrangement of the precaval band and the interatrial wall are comparable in the swine heart (Figure 2). In the human heart, however, it is not only the terminal crest that merges into the anterior interatrial wall to become Bachmann's bundle; the rightward rim of the superior interatrial fold, itself continuous with the wall of the superior caval vein, is also made up of cardiomyocytes aligned in parallel fashion. And, like the precaval band, these aggregated entities also merge with Bachmann's bundle (Figure 1, panel B). The significance of these additional components of the atrial walls to interatrial conduction had been emphasized in a recent study by the group working in Rotterdam.¹¹ As can be seen by comparing Figures 1 and 2, the arrangement is subtly different in the swine heart, since the rims of the oval fossa are not directly related to the area recognizable as Bachmann's bundle (Figure 2B). What is obvious in the sections of both the human and swine hearts, nonetheless, is the parallel alignment of the atrial cardiomyocytes aggregated together to produce Bachmann's bundle (Figures 1B and 2A).

The walls of the atrial chambers are frequently described as being made up of myocardial "fibers". We have used the term "fiber" in this fashion in many of our own previous publications. We are now aware, however, that the working unit of the myocardium is the cardiomyocyte. It is the fashion in which the cardiomyocytes are aggregated together that produces the "grain" that can be demonstrated by dissections that remove the epicardial surface of the atrial wall. Although showing this obvious "grain", there are no discrete "muscles" that can uniformly be demonstrated within the walls, such as a "septopulmonary bundle". Cardiac muscle is fundamentally different from skeletal muscle in that the cardiomyocytes are not arranged with discrete origins and insertions. The allegedly separate parts of the atrial walls described as "bundles" are no more than aggregated components of mural entities, albeit that the cardiomyocytes themselves can be aggregated together in different alignments within the layers of the walls. It is the overall manner of aggregation, nonetheless, that is responsible for the anisotropic conduction known to occur throughout the walls. As was recognized by Lewis, Meakins, and White,⁴ conduction occurs much more rapidly along the long axis of cardiomyocytes aggregated in parallel fashion than it does in the short axis of such aggregated entities. Indeed, the mere presence of longitudinally aggregated cardiomyocytes can produce discontinuity in transverse conduction.

It is not possible, of course, to determine the properties of a cardiomyocyte to conduct by examining it with a microscope. This fact is pertinent to some of the suggestions that have been made in favor of "specialization" of atrial cardiomyocytes. The group from Vermont, in their recent clinical study,⁷ have pointed to the suggestion of Sherf and James regarding the presence

of different "cell types" relative to potential specialization.¹² Sherf and James were concerned predominantly with establishing the "specialization" of the internodal tracts, although they recognized the similarity of their proposed tracts to Bachmann's bundle. The criteria used by James and his colleagues had been discussed and disputed in great detail.¹³ The review was published in the European Journal of Cardiology,¹³ which subsequently became the International Journal of Cardiology. The manuscripts published in its initial incarnation, sadly, are no longer available for online scrutiny. The arguments relative to histology, nonetheless, were revisited in the recent investigation published in this journal, which emphasized the role of parallel aggregation of working atrial cardiomyocytes.³ Those arguing in favor of "specialization" also cite the study of Wagner and colleagues, in which "plateau" potentials were recorded from some of the cardiomyocytes of Bachmann's bundle.¹⁴ They neglected to cite the evidence showing that working atrial cardiomyocytes are fully capable of producing such "plateau" action potentials.¹⁵ As was discussed in the recent review of the topic published in the Journal,³ it is certainly possible that some particular feature of the cardiomyocytes aggregated together to form the internodal pathways and Bachmann's bundle, over and above their parallel alignment, could contribute to the known preferential conduction across the pathways.¹ As yet, any such feature has not been unequivocally identified using light or electron microscopy, or microCT interrogation. Newer techniques, such as laser capture histology, or transcriptomics, may well identify such features. Until such new evidence becomes available, there is no reason to doubt that the parallel aggregation of the individual working atrial cardiomyocytes, as suggested by Lewis, Meakins, and White,⁴ is more than capable of functioning as the substrate for rapid interatrial conduction.

None of this speculation questions the value of the study of Lustgarten and colleagues in identifying the site for pacing Bachmann's bundle to achieve optimal atrial resynchronization,⁷ which is confirmed by Yoshimoto and colleagues⁹. Such selective pacing is now to be greatly preferred over the traditional approach of pacing the right atrial appendage.⁹

References cited

1. Bachmann G. The inter-auricular time interval. *Am J Physiol.* 1916; 41: 309–320
2. Duong NC, Yang Z, Iaizzo PA. Anatomical, electrical, and hemodynamic characterization of Bachmann's bundle within the swine heart. *Heart Rhythm* 2025; in the press
3. Anderson RH, Sánchez-Quintana D, Spicer DE, Farré J, Sternick EB. How does the cardiac impulse pass from the sinus to the atrioventricular node? *Heart Rhythm.* 2022; 19: 1738-46.
4. Lewis T, Meakins J, White PD. The excitatory process in the dog's heart. Part I.—The auricles. *Philosophical Transactions of the Royal Society of London. Series B, Containing Papers of a Biological Character.* 1914; 205: 375-420.
5. Eyster JAE, Meek WJ. Experiments on the origin and propagation of the impulse in the heart *Heart.* 1914; 5:137-140
6. James TN. The connecting pathways between the sinus node and AV node and between the right and the left atrium in the human heart. *American Heart Journal.* 1963; 66: 498-508.
7. Lustgarten DL, Habel N, Infeld M, et al. The Bachmann Bundle Pacing Target - retrograde mapping and microstructural correlation. *Heart Rhythm.* 2025, in the press
8. Lustgarten DL, Habel N, Sánchez-Quintana D, et al. Bachmann bundle pacing. *Heart Rhythm.* 2024; 21: 1711-7.
9. Yoshimoto Y, Sakamoto Y, Uemura Y, et al. Comparative assessment of interatrial conduction delay during Bachmann's bundle pacing and right atrial appendage pacing using biatrial strain rate echocardiography. *Heart Rhythm.* 2025 <https://doi.org/10.1016/j.hrthm.2024.12.016>
10. Saremi F, Channal S, Krishnan S, et al. Bachmann bundle and its arterial supply: imaging with multidetector CT—implications for interatrial conduction abnormalities and arrhythmias. *Radiology.* 2008; 248: 447-57
11. Knol WG, Teuwen CP, Kleinrensink GJ, et al. The Bachmann bundle and interatrial conduction: comparing atrial morphology to electrical activity. *Heart Rhythm.* 2019 Apr 1;16(4):606-14.

12. Sherf L, James TN. Fine structure of cells and their histologic organization within internodal pathways of the heart: clinical and electrocardiographic implications. *Am J Cardiol.* 1979; 44: 345-69.
13. Janse MJ, Anderson RH. Specialized internodal atrial pathways: fact or fiction. *Eur J Cardiol.* 1974; 2: 117-36.
14. Wagner ML, Lazzara R, Weiss RM, Hoffman BF. Specialized conducting fibers in the interatrial band. *Circ Res* 1966; 18: 502-18.
15. Anderson RH, Becker AE, Trandum-Jensen J, Janse MJ. Anatomico-electrophysiological correlations in the conduction system - a review. *Br Heart J.* 1981; 45: 67-84.

Legends to Figures

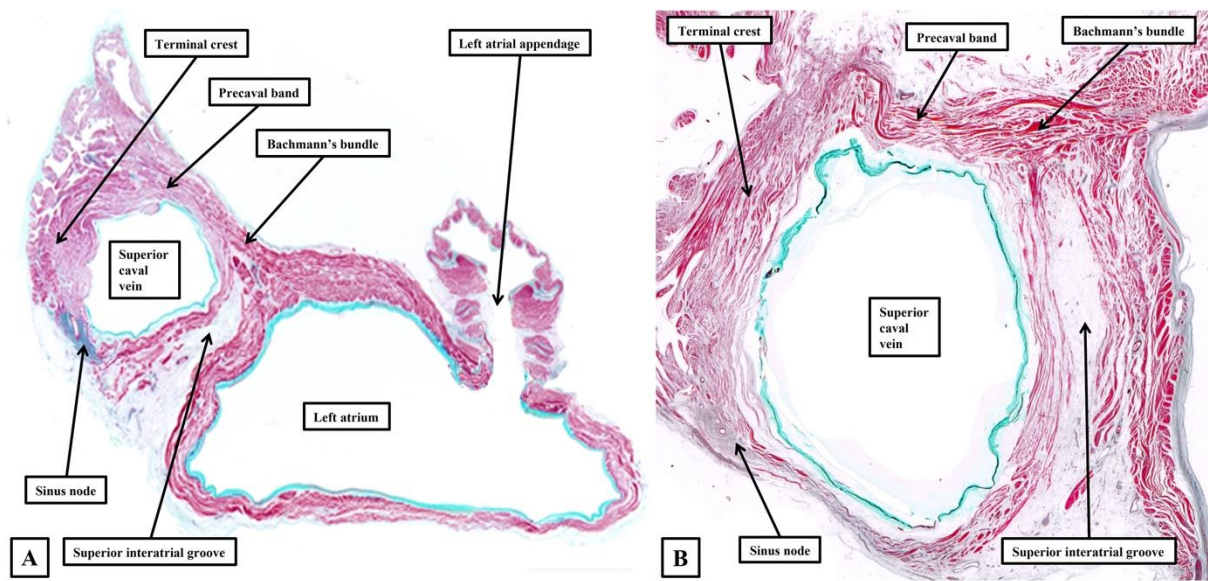


Figure 1. The panels show histological sections, taken in the short axis of the atrial chambers, from different human hearts, but with both sections stained using the trichrome technique. Panel A shows the overall arrangement of the pathway that incorporates Bachmann's bundle. The terminal crest passes in front of the orifice of the superior caval vein as the precaval band. It then becomes part of the anterior interatrial wall as Bachmann's bundle, with the contained cardiomyocytes continuing with their parallel alignment to the origin of the left atrial appendage. Note also how the staining permits recognition of the site of the sinus node. Panel B, from a different human heart, but taken at higher magnification, shows better the parallel alignment of the working atrial cardiomyocytes aggregated together to form the terminal crest, the precaval band, and Bachmann's bundle. Note also the similar parallel aggregation of the cardiomyocytes making up the walls of the superior interatrial groove. Using light microscopy, there is nothing "special" that can be distinguished with regard to the cardiomyocytes making up Bachmann's bundle other than their parallel alignment.

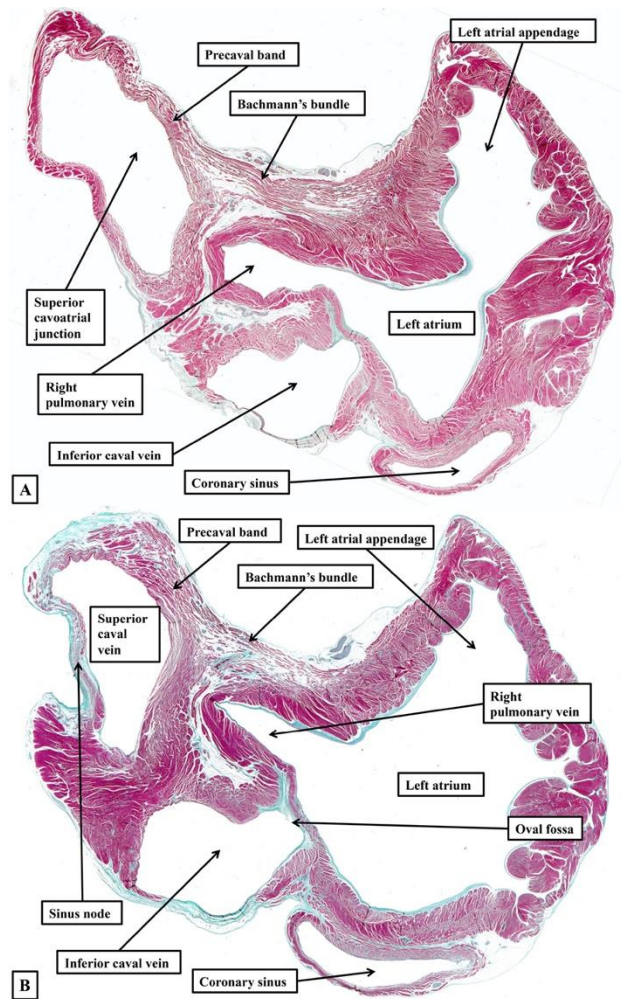


Figure 2. The images show the features of serial histological sections prepared from a swine heart and stained using the trichrome technique. The section shown in panel A is cranial to that demonstrated in panel B. As with the human heart (Figure 1B), the working atrial cardiomyocytes are aggregated together in parallel fashion to produce Bachmann's bundle, which is a direct continuation of the precaval band. Unlike the arrangement in the human heart, however, it is not possible, from the sections, to identify a prominent terminal crest. It is still possible, nonetheless, to distinguish the specialized cardiomyocytes making up the sinus node. Note, however, that the margins of the oval fossa, unlike the arrangement in the human heart, are not directly related to the anterior interatrial wall.