Anatomic-Electrophysiological Correlations Concerning the Pathways for Atrioventricular Conduction

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Special Report

Anatomic-Electrophysiological Correlations Concerning the Pathways for Atrioventricular Conduction

Todor N. Mazgalev, PhD; Siew Yen Ho, PhD; Robert H. Anderson, MD

Abstract—The remarkable success of radiofrequency ablation in recent decades in curing atrioventricular nodal reentrant tachycardias has intensified efforts to provide a solid theoretical basis for understanding the mechanisms of atrioventricular transmission. These efforts, which were made by both anatomists and electrophysiologists, frequently resulted in seemingly controversial observations. Quantitatively and qualitatively, our understanding of the mysteries of propagation through the inhomogeneous and extremely complex atrioventricular conduction axis is much deeper than it was at the beginning of the past century. We must go back to the initial sources, nonetheless, in an attempt to provide a common ground for evaluating the morphological and electrophysiological principles of junctional arrhythmias. In this review, we provide an account of the initial descriptions, which still provide an appropriate foundation for interpreting recent electrophysiological findings. (***Circulation***. 2001;103:2660-2667.)

Key Words: anatomy ■ electrophysiology ■ atrioventricular node

It is perhaps paradoxical that as we begin the next century, we are still arguing about the structure and function of the substrates for atrioventricular conduction. It is just over 100 years since suggestions were first made concerning the existence of "special" muscular bridges that ran between the atrial and ventricular chambers of the heart.[1,2] It is a few years less than 100 since the anatomic features of the solitary normal muscular pathway for conduction were clarified.[3] However, arguments continue regarding the anatomic structure of the specialized muscular axis[4,5] and, in particular, the parts of the muscular bridge that malfunction in the settings of arrhythmia and reentry. We should be aware of the aphorism concerning the fate of repeating past mistakes if we do not learn from them. And there is ample evidence, at least for morphologists, of the mistakes made in those earlier periods during the discovery of the anatomic pathways. In this review, we first give an account of the initial descriptions.[1–3,6] As we will show, these descriptions still provide the appropriate foundation for the interpretation of recent electrophysiological findings. We then suggest how this anatomic arrangement might set the scene for understanding conduction through the atrioventricular node, despite the fact that the precise anatomic substrates for the well-recognized concept of dual atrioventricular nodal physiology[7] still remain to be elucidated.

Historical Precedent

The 2 studies that appeared in 1893 and first proposed the existence of specialized muscular atrioventricular bridges were markedly dissimilar. Kent[1] argued that in the normal heart, there were multiple muscular bridges that crossed the insulation provided at the atrioventricular grooves. Although subsequently proved incorrect in terms of anatomy, this misconception served an important role in permitting Mines[8] to predict the existence of reentry; this phenomenon was subsequently shown to be the basis of Wolff-Parkinson-White syndrome. The other publication from 1893, that of His,[2] was much closer to the mark, even if it was not well understood at the time. Arthur Keith, the discoverer of the sinus node, described in his autobiography[9] how he was asked by Mackenzie to examine His's account of the specialized muscular atrioventricular connection. After his initial studies, Keith was unable to verify His's findings. Rather, he expressed himself skeptical of the existence of an atrioventricular bundle. Then, Mackenzie furnished him with a copy of the recently published monograph "Das Reitzleitungssystem des Saugetierherzens."[3] Guided by this book, Keith was able to confirm the existence of the histologically specialized muscular pathway responsible for normal atrioventricular conduction.[10] As Keith rightly stated "with the publication of the work of Tawara, heart research entered a new epoch."[9]

Tawara's[3] achievement was to show that a system of histologically distinctive muscular fibers extended from the base of the atrial septum, penetrated the atrioventricular insulating fibrous plane, and ramified on the sides of the muscular ventricular septum to form networks of Purkinje fibers at the ventricular apexes (Figure 1). He also showed how the bridging system commenced in atrial transitional cells, gathering itself together into a compact node, or "knoten," before penetrating the insulating tissues to become
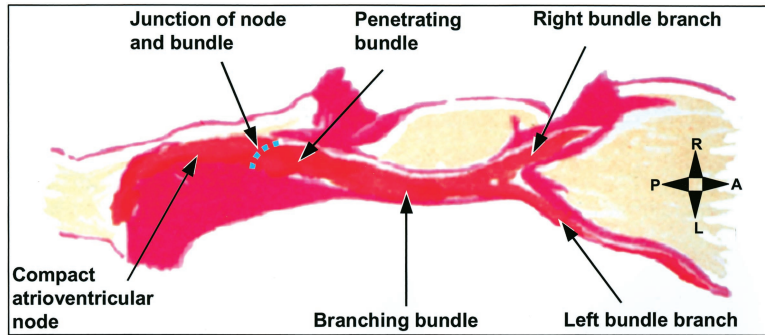
Figure 1. This figure was scanned from the original drawing by Tawara[3] and reoriented in an attitudinally correct fashion. It shows the different components of the atrioventricular conduction axis as discovered by Tawara.[3] The labels have been added to assist in providing clarity. The "compass" shows orientation (P indicates posterior; A, anterior; L, left; and R, right).

the bundle previously recognized by His. Significantly, Tawara commented on the difficulties encountered by the histologist in using details of cellular structure to distinguish those components of the axis that could be described as node in contrast to bundle. Indeed, because of these difficulties, Tawara proposed that the distinction was better made using an anatomic criterion, namely the point at which the axis entered the central fibrous body to become the penetrating bundle, or the bundle of His. As we will see, this criterion retains not only its validity, but also its currency.

Shortly after having read Tawara's account and having confirmed the existence of the atrioventricular conduction axis, Keith made his own epochal contribution, namely the discovery of the sinus node.[6] The existence of this structure was soon confirmed by other investigators, notably Walter Koch,[11] who also provided an excellent depiction of the anatomic location of the 2 nodes (Figure 2). It was not long, however, before a suggestion was made that further special
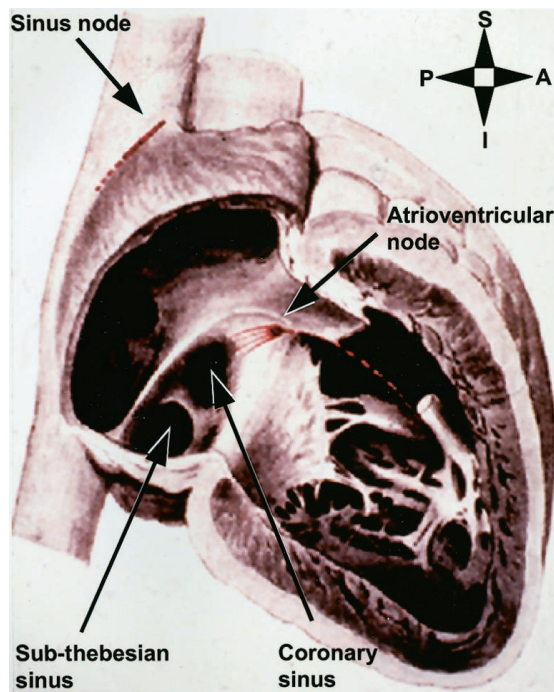
pathways could be traced through the atrial myocardium, specifically along the terminal crest, to provide a direct muscular tract from the sinus to the atrioventricular node. This suggestion, which was made by Thorel,[12] was treated with sufficient gravity by the German Society of Pathology that the topic was the subject of specific debate at their 1910 meeting, which was held in Erlangen. From this meeting emerged a set of criteria, proposed by Aschoff[13] and Monckeberg,[14] for the recognition of anatomically specialized tracts for intracardiac conduction. These distinguished investigators argued that it had been established beyond doubt that the paradigm of a pathway for conduction was Tawara's muscular bridge. Using the ventricular components of this system as their example, they proposed 3 criteria for specialization; these were that the cells of the purported tract should be histologically discrete, that it should be possible to follow them from section to section, and most importantly, that they should be insulated by fibrous sheaths from the nonspecialized adjacent working myocardium.

Historical Precedents Revisited

Multiple investigators have reexamined the cardiac conduction system since these early descriptions. Most findings, including our own, have been supportive and confirmatory of the original accounts. Some have been more revisionary; these works include those that in recent years have claimed to have shown tracts of cells either extending between the cardiac nodes[15] or providing discrete inputs into the atrioventricular node.[4,16] It is significant that those claiming to have found these tracts use their purported findings to explain physiological phenomena, such as "sinoventricular conduction" (see Reference 17 for review) or dual pathways within the atrioventricular node.[7] The latter topic is now the more important as searches continue for the elusive anatomic substrate of the slow pathway into the atrioventricular node. It is timely, therefore, to reexamine the arrangement of the atrial myocardium in the light of the criteria provided by Tawara,[3] Aschoff,[13] and Monckeberg[14] and to establish how these anatomic findings set the scene for understanding electrophysiological observations. In this light, it must be remembered that the specialized conduction tissues are invisible to the naked eye. Their location is established only by careful histological examination, which must include serial sectioning of the areas under investigation; this is ideally combined with 3D reconstruction to establish the precise

Figure 2. This figure from the work of Koch,[11] which was initially unlabeled, shows the location of the cardiac nodes in attitudinally correct orientation. The labels have been added to aid in clarity. Orientation is shown by the "compass" (P indicates posterior; A, anterior; S, superior; and I, inferior).
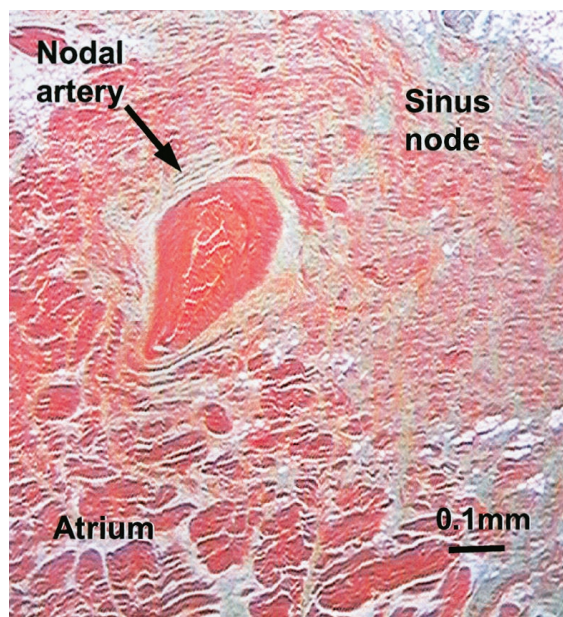
Figure 3. Photomicrograph of the sinus node from the adult human heart. The cells of the sinus node are histologically distinct and set in a firm fibrous matrix, but they are not insulated from the adjacent working atrial myocardium.

extent and disposition of the recognized histologically specialized tissues.

Such examination shows that the cells making up the sinus node fulfill only 2 of the criteria established by Aschoff[13] and Monckeberg.[14] The node is discrete because it is made up of networks of small cells closely packed in a dense matrix of fibrous tissue. In humans, these nodal cells are usually, but not always, arranged around the prominent artery to the sinus node (Figure 3). Examination of serial sections reveals the extent of the node and shows that, at its margins, only small tongues of histologically specialized cells extend into the adjacent working myocardium. The ordinary atrial musculature is composed of much larger cells set in a less dense collagenous matrix. The cells of the sinus node, however, although embedded in fibrous tissue, are not insulated from the working cells. Indeed, such insulation, if it existed, would defeat the purpose of the sinus node, which is to act as the cardiac pacemaker. To achieve this purpose, the nodal cells must communicate freely with the working cells, and they do this through the small zones of transitional cells found at the margins of the node itself. The functional correlates of this anatomic arrangement have been well documented (see Reference 18 for review).

To establish the arrangement of the atrial myocardium, it is again necessary to study serial histological sections and, ideally, to study these sections when obtained from blocks encompassing the entire right atrial chamber. Only in this fashion is it possible to study the tissue relative to the criteria of Aschoff[13] and Monckeberg[14] and to follow, section by section, the cells that make up the internodal atrial myocardium. Studies conducted in this fashion, studying the entire right atrial myocardium in a single block of tissue, have failed to reveal the presence of insulated tracts of histologically specialized myocardium linking the sinus and atrioventricular

nodes (see Reference 18 for review). Instead, these studies and others[19] show that it is the nonuniform anisotropic alignment of the myocardial cellular bundles that accounts for preferential conduction within the atrial myocardium. Indeed, as long ago as 1916, Bachmann[20] offered this explanation for the parallel packing of ordinary atrial myocardial cells to account for preferential conduction along the interatrial bundle that now bears his name.

More recently, tracts of cells have been observed within the atrial tissue delineated by immunocytochemical markers such as HNK-1 or Leu-7.[21] These tracts, however, are widely spread throughout the atrial tissues, including the appendages, and their histological specificity is transient.[22] The cells identified using these techniques do not fulfill the criteria of Monckeberg[14] and Aschoff[13] for recognition as conducting tracts. Likewise, these cells, which provide the substrate for sinoventricular conduction, as yet have no known anatomic substrate. It may well be that, in the future, quantitative studies will show that these cells are distinguished according to their connexins or have characteristic ion channels. At present, however, it is the criteria of Aschoff[13] and Monckeberg[14] that provide the best anatomic definition of histological specialization.

What then, when viewed in this light, of the atrioventricular node and its nodal approaches? We must begin our discussion of this topic by reemphasizing our criteria for recognizing the distal extent of the node, because it is different interpretations of this point that underscore recent controversies.[4,5,16] As we have already indicated, Tawara himself[3] commented on the problems encountered by the histologist in distinguishing between the compact node, or "knoten," and the penetrating bundle of His. Because of the difficulties inherent in accurately making the distinction histologically, Tawara proposed an anatomic definition for the transition from node to bundle. We must then state that we have not ourselves always used this definition. Thus, when making a detailed anatomic-electrophysiological correlation in the rabbit node, we described the area that was most complex histologically as the "closed atrioventricular node," because it was insulated within the central fibrous body.[23] Racker and Kadish[16] similarly described the atrioventricular node as enclosed within the insulating fibrous tissues of the atrioventricular junction. Within the criterion proposed by Tawara,[3] this insulated part of the pathway for atrioventricular conduction is best described as part of the penetrating atrioventricular bundle. It is the failure to follow this definition that produces the apparent discrepancies in some recent accounts[4,16] when compared with "traditional" understanding.[22]

The atrioventricular node, therefore, is an integral part of the atrial musculature (Figure 4), in contrast to the atrioventricular bundle, which is insulated within the so-called central fibrous body (Figure 5). The atrioventricular bundle is the first part of the ventricular conducting pathway and the first structure we have considered thus far that satisfies all 3 of the histological criteria proposed for a specialized conduction tract. The cells within the bundle are histologically discrete, the bundle can be traced from section to section and, most importantly, the fibrous tissue from the adjacent myocardium insulates the cells within the bundle. These criteria continue to hold good for the more distal parts of the ventricular
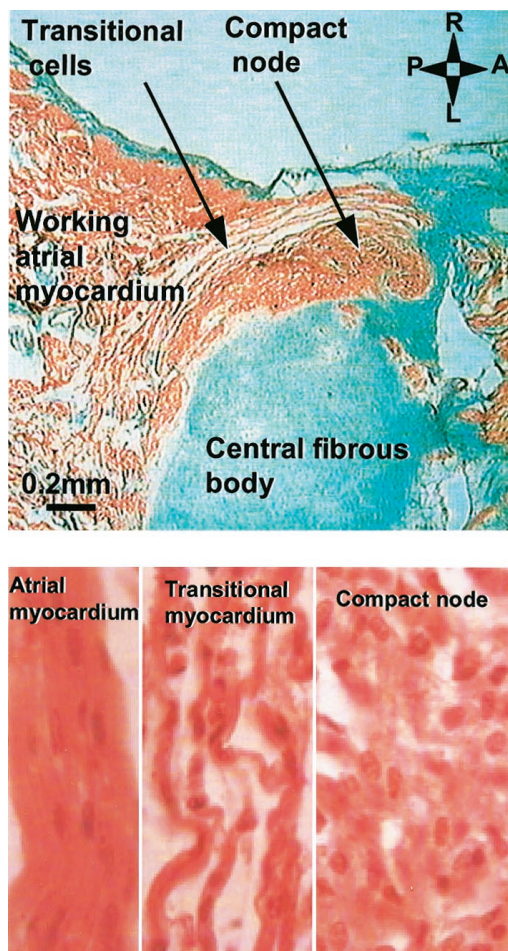
Figure 4. The top panel shows the atrial components of the specialized axis responsible for atrioventricular conduction (compare with Figure 1). The bottom panels are magnifications of the cells of the working atrial myocardium, the transitional envelope, and the compact node. None of these tissues is insulated from its neighbors. The "compass" shows orientation (abbreviations as in Figure 1).

pathways, which are insulated from the adjacent working ventricular myocardium until the Purkinje cells ramify into the myocardium within the ventricular apexes. The atrioventricular node, like the sinus node, satisfies only 2 of the histological criteria for specialization. Its cells are morphologically distinct, forming interconnecting meshes set in a prominent fibrous matrix. They can also be traced from section to section, thus permitting distinction of 2 inferior extensions of the compact node. The extent of these inferior horns varies according to age.[24] This variation may well prove to be significant with regard to the anatomical substrate for the slow pathway.

Also potentially significant in this regard is the fact that, at the margins of the compact node, it is possible to recognize further limited zones of cells, which again satisfy 2 of the criteria required for histological specialization. Called the transitional cells, these cells are intermediate in their morphology between the cells of the compact node and the working atrial myocytes. An envelope of these transitional cells interposes between the right surface of the half-oval of

the compact node, when seen in its own short axis, and a second envelope of working atrial myocardium. The latter envelope then extends into the vestibule of the tricuspid valve. Short zones of transitional cells also interpose between the left margin of the compact node and the myocardium on the left side of the atrial septum. More extensive zones of transitional cells, seen as attenuated bundles of small cells separated by curtains of collagenous tissue, extend inferiorly and posteriorly toward the mouth of the coronary sinus and the so-called Eustachian ridge. Apart from these zones of histologically discrete transitional cells, which always interpose between the cells of the compact node, its extensions, and the working atrial myocytes, there are no additional collections of cells that can be recognized on the basis of their histology as emanating from the nodal tissues. In particular, it should be noted that the recently described "atrionodal bundles"[4,16] fail to satisfy the criteria established by Aschoff[13] and Monckeberg.[14]

If we summarize the situation morphologically, therefore, excellent criteria were established in the first decade of the last century to permit histological distinction of the specialized conduction tissues.[13,14] Two of these criteria need to be fulfilled to justify descriptions of cardiac nodes or transitional cells, while all 3 need to be fulfilled if a purported collection of cells is to be considered a tract specialized morphologically for conduction. The criterion established even earlier by Tawara[3] then permits distinction of the atrial components of the atrioventricular conduction pathway from the penetrating atrioventricular bundle of His. No evidence provided subse-
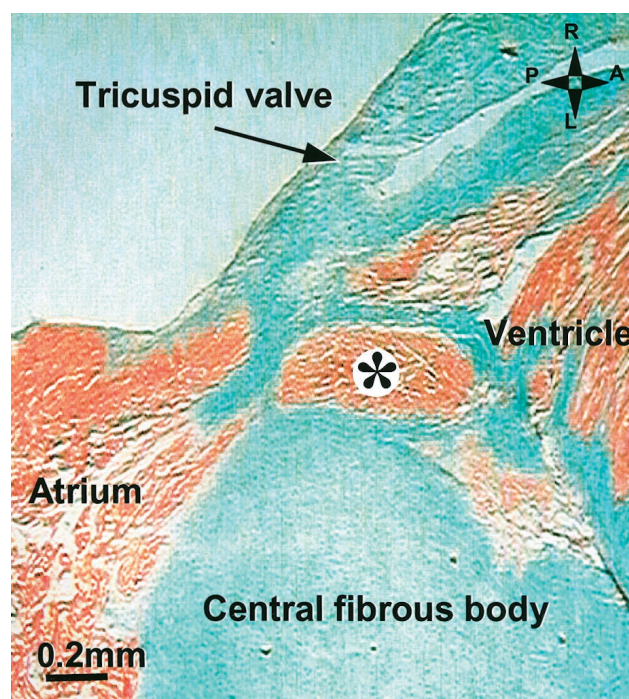

Figure 5. This section, from the same series as Figure 4, shows the penetrating atrioventricular bundle (*). This part of the conduction axis is insulated within the fibrous tissue of the central fibrous body. This is the feature that makes it into a conducting tract. The "compass" shows orientation (abbreviations as in Figure 1).

quent to these initial works, to the best of our knowledge, has questioned their adequacy or shown them to be in need of modification.

The Morphological-Electrophysiological Bridge

The division of the atrioventricular nodal region into several zones is a convenient simplification that usually juxtaposes 3 morphological subregions, namely the transitional, midnodal, and lower regions with 3 cellular subtypes, designated AN (atrionodal), N (nodal), and NH (nodal-His), respectively, as originally described by Paes de Carvalho and De Almeida in 1960 (due to space limitations, detailed references to the seminal works of these authors and to those of B.F. Hoffman, P.F. Cranefield, M.S. Spach, and other founders of the modern atrioventricular node electrophysiology can be found in Reference 25). Unfortunately, this subdivision is not based on morphological specificity and has electrophysiological currency only for the rabbit node.

Thus, the midnodal part of the axis has been vaguely described as an area of densely packed cells[25] with relatively small size and varying orientation. It exists as a basket-like structure imposed between the bundle of His and the loose atrial approaches to the node. As noticed by Tawara[3] and emphasized above, the boundaries of the compact node are not sharply defined. Similarly, the electrical responses of the nodal cells are not unique. Thus, action potentials with similarly small resting membrane potentials, small time-derivatives of the upstroke (dV/dt), and amplitudes can be recorded from the area of the compact node and from fibers, which are conveniently termed "nodal-like," that are found in the nodal approaches.[26] The atrionodal cells are potentially correlated with transitional cells. These cells, although morphologically different from the working atrial fibers, are widely spread within the nodal approaches and are intermingled with the even smaller nodal cells in the compact region. A more distinct electrical and morphological specialization is seen in the progressively distal nodal-His and His fibers.

The difficulties in providing precise morphological-electrophysiological descriptions are in part determined by the lack of appropriate techniques for simultaneous examination of the electrical responses and the structure of the same fiber.[25] Electrical properties of cells isolated from the atrioventricular node have been studied,[27] but the precise region from which they were harvested remained unknown.

The Duality of Atrioventricular Nodal Electrophysiology

Moe and associates[7,28] provided evidence for what they described as a dual-conduction system in the hearts of dogs and rabbits. This concept was soon applied to the human heart.[29] A simplified definition of the dual-pathway electrophysiology assumes that more than one wavefront exists at a given time in the triangle of Koch. Depending on the atrial prematurity and when specific functional requirements are met, such as unidirectional block and slow propagation, the concept of dual pathways provides the basic mechanisms for understanding longitudinal dissociation of conduction and sustained reentrant tachycardia that either involves the atrial
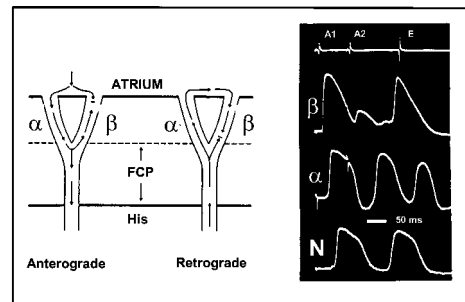

Figure 6. Illustration of the concept of 2 longitudinal pathways, α and β, to explain the formation of a reciprocation loop during anterograde or retrograde propagation. FCP indicates the final common pathway. The microelectrode recordings (right) demonstrate conduction block after the premature atrial beat A2 in pathway β (the low-amplitude electrotonic hump in the second trace). The α-domain, however, was successfully depolarized (the second action potential in the third trace). This latter wavefront subsequently invaded, apparently retrogradely, the β-pathway and produced an atrial echo beat (E). The activation of the distal nodal cell (the fourth trace) after the premature beat A2 apparently resulted from propagation via the α-pathway. Modified from Reference 28.

myocardium in the reentry loop[30] or uses a circuit for reentry that is confined exclusively within the atrioventricular node.[31] Direct demonstration of intranodal reentry by high-resolution mapping in the canine heart during ventricular echo beats was provided recently by Loh et al.[32]

The equalization of dual-pathway electrophysiology with the discrete $\alpha\beta$ model,[28] although imprecise, simplified the concept of cycle length–dependent nodal transmission (Figure 6). Furthermore, it suggested the possibility of interrupting the reentrant circuit by appropriately localized lesions and thus presaged the era of radiofrequency ablation.

Although the specialized components of the atrioventricular node communicate with the atrial myocardium through connections running in virtually all directions,[33] 2 major inputs have been specifically described as having special functional importance. The inferoposterior input, or approach, encompasses the 2 isthmuses, located inferiorly and septally, whereas the superoanterior input refers to the broader area of the superior approaches from the interatrial septum.

During typical reentry tachycardia, anterograde atrial-His conduction that proceeds via the inferior portion of the reentry loop is substantially longer ("slow") than is the retrograde conduction via the superior, or "fast," pathway. By extension, the relatively short delays observed within the node during sinus rhythm are thought to result from anterograde conduction through the fast pathway. Although seemingly logical, the terms fast and slow are entirely arbitrary. As yet, no convincing evidence has been provided for either different or identical velocities of conduction in the functionally dissociated pathways.[34]

Morphology and Duality of Atrioventricular Nodal Propagation: A Simplified Model

As argued earlier in this review, the return to the original interpretation of Tawara[3] provides the best means of reconciling seemingly controversial morphological and electro-
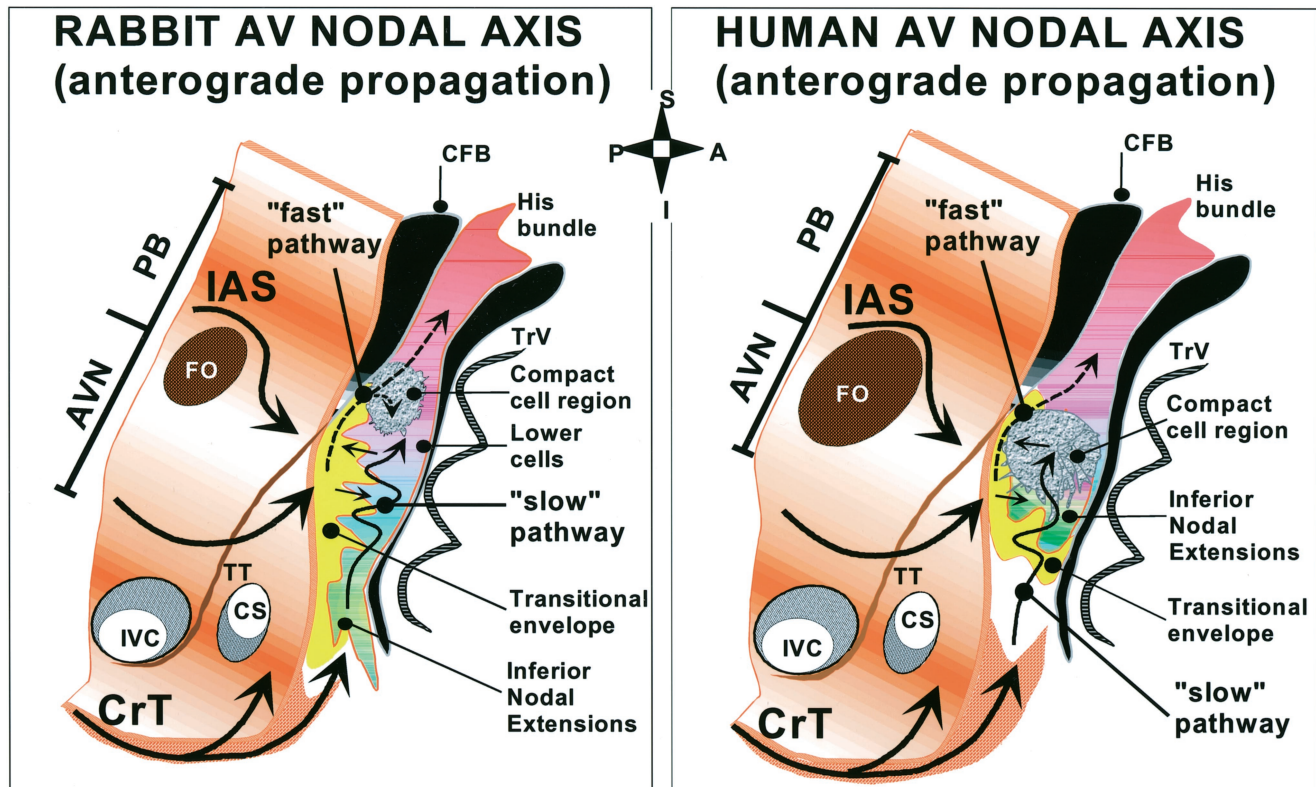
Figure 7. Model illustrating some features of the dual-pathway atrioventricular nodal electrophysiology in the rabbit (left) and human (right) heart. The region of the triangle of Koch is shown in attitudinal orientation. A "cut" above and along the tricuspid valve opening has been made at an angle to the endocardium to reveal the underlying structures of the conduction axis. See the text for discussion. AVN indicates atrioventricular node; PB, penetrating bundle; CFB, central fibrous body; FO, fossa ovalis; TT, tendon of Todaro; IVC, inferior vena cava; CS, coronary sinus; CrT, crista terminalis; IAS, interatrial septum; and TrV, tricuspid valve. Orientation is shown by the "compass" (P indicates posterior; A, anterior; S, superior; and I, inferior). Wavy arrow indicates slow pathway; dashed arrow, fast pathway; small left-to-right arrows, electrical impulses from directions other than inferior; small right-to-left arrows, reentrant exit. Modified from Mazgalev TN, Tchou PJ, eds. *Atrial-AV Nodal Electrophysiology: A View From the Millennium*. Armonk, NY: Futura Publishing; 2000:224.

physiological interpretations. In view of the lack of convincing evidence for insulated conducting bundles interposed between the working atrial myocardium and the node that might serve as fast and slow channels, we propose to apply the principle of functional dissociation to both the electrophysiological and the morphological substrates.

The specialized conduction axis is surrounded by plain atrial fibers having variable orientations.[33] This endocardial anisotropy is responsible for an inhomogeneous pattern of activation in the triangle of Koch. The prematurity and direction–dependent conduction delay in the endocardial layer, however, has been shown to be negligible in comparison with the delay produced within the node, thus making it unlikely that this structural peculiarity of the atrial approaches is the substrate for the dual pathways.[35] As an alternative, Waki et al[24] focused attention on the inferior extensions of the compact node as a possible substrate for the slow pathway. Although less intensely studied, the loose transitional fibers that connect the node with the superior approaches may represent another domain that is functionally important only at long coupling intervals and that can thus support the fast wavefront.

The 2 panels in Figure 7 refer to the rabbit and the human heart. The penetrating bundle and the atrioventricular node are defined using Tawara's definition and landmarks,[3] so that

the node represents the noninsulated, nonpenetrating portion of the axis that is activated from the atrial myocardium. In humans and dogs, the compact region is proximal to the well-defined edge of the fibrous collar. In the rabbit, the knot of compact cells is part of the penetrating bundle, as defined by Tawara.[3]

The fibers of the penetrating bundle in the rabbit extend posteriorly and inferiorly beneath the compact region, emerging into the atrial tissues where this structure, now called the lower cells but no longer insulated, is making contact with atrial tissue via an envelope of transitional cells. These inferior nodal extensions are pronounced in the rabbit heart, in which they can be traced on the basis of their histology into the vestibule of the tricuspid valve, providing the input to the node via the terminal crest. In contrast, inferior nodal extensions seem to be a less-pronounced feature of the human heart,[33] providing for a substantial gap filled by nonspecialized myocardium in the vestibule between the coronary sinus and the tricuspid valve. It should be noted that the proportional length of the extensions varies with age in the human heart.[24]

Atrial cells do not communicate directly with the compact and/or lower cells, but only through the intermediate transitional cells. The distal margins of the envelope of transitional cells, which is in contact with the compact region, are

themselves covered by the thinning marginal central fibrous tissue, which at this level exhibits numerous areas of deficiency. Although the nodal cell fibers are intermixed with fat and connective tissue, neither the transitional envelope nor the lower nodal tracts are electrically insulated; therefore, they should not be viewed as homogeneous, cable-like structures.

The Putative Slow Pathway Domain

The conduction that proceeds along the inferior nodal extensions and through the lower nodal cells forms the slow pathway (Figure 7). This leads toward the region of compact cells and further into the penetrating bundle. The term slow, although not yet justified by direct measurement, seem appropriate for 2 reasons. First, the pathway encompasses the entire length of the nonpenetrating axis. In general, this would require a longer time to transverse. Second, the pathway is composed of nodal or nodal-like cells with specific electrophysiological properties that are responsible for a slow velocity of conduction. Conduction through the slow pathway should not be associated exclusively with activation through the inferior input, because the transitional envelope can also provide an electrical impulse from other directions. Furthermore, the slow propagation through the lower cells may support a reentrant exit anywhere along the transitional envelope.

The clinical procedure of slow pathway ablation, which is performed in the isthmus between the coronary sinus and the tricuspid valve, may not necessarily eliminate the slow pathway domain. The ablation may inflict its damage on the plain atrial tissue forming the gap between the inferior nodal approaches and the node itself.[33] Thus, slow pathway ablation may very well coexist with preservation of the dual-pathway electrophysiology, as has been demonstrated clinically.[36]

The Putative Fast Pathway Domain

The broad fast wavefront has its source(s) in the activation of the transitional envelope at long coupling intervals. Some experimental evidence[37] suggests that more than one functional wavefront may exist in this domain. Ultimately, however, the propagation proceeds toward the most superior extensions of the transitional cells (Figure 7). There, a short transverse route may be formed through a portion of the compact region into the penetrating bundle. The adjective fast would then reflect the short atrial-to-His delay observed at slow rates. Functionally, however, this domain may not support high velocities of conduction and, in fact, it is characterized by a low safety factor, as recognized clinically. Furthermore, it may be extremely difficult to ablate the fast pathway selectively. On the basis of a proposed model, lesions on the transitional envelope, especially where it comes in close contact with the compact cells, are likely to produce conduction block.

Because the slow and the fast pathway domains are not insulated channels, intercommunication between the wavefronts can be expected. The fast wavefront running on the surface can exert an electrotonic depressive effect on the deeper nodal structures.[38] Similarly, clinical observations

suggest that ablation of the slow pathway may modulate the refractory properties of the remaining fast wavefront.[39]

It is tempting to suggest that some properties of the dual-pathway electrophysiology might be dependent on the architecture of the conduction axis. Thus, transition between conduction through the fast and slow pathways in the rabbit is usually smooth, whereas in humans, the conduction curve frequently exhibits a "jump." A substantial difference in the arrival times of the 2 wavefronts may occur if the fast wavefront "pierces" directly from the transitional envelope through a small part of the compact cells into the penetrating bundle, while the slow wavefront transverses the entire compact region (Figure 7). No morphological data are currently available, however, to compare the conduction axis in subjects with and without nodal reentry tachycardia. We assume, therefore, that the dual-pathway physiology is a general property of atrioventricular conduction that can be manifested in sustained reentrant activation under appropriate structural and/or functional conditions.

Conclusion

While reexamining the classic foundations of the morphology of the atrioventricular conduction axis, we attempted to provide a new point of view on the controversial concept of the duality of the nodal electrophysiology. Our proposal is not revolutionary, because it accommodates many of the fundamental principles introduced by earlier investigators. Our concept of the dual electrophysiological pathways is based on separate wavefronts that propagate in functionally dissociated, rather than electrically insulated, domains. The envelope of the transitional cells and a brief trespass through the compact nodal region in the anterior margin of the triangle of Koch may constitute the domain of the fast wavefront. The deeper inferior/posterior extensions and the compact region are the proposed domain of the slow wavefront.

Neither the current morphological evidence nor the existing knowledge of the complex cellular electrophysiology provides definitive answers to a number of questions. It is unclear if the structural differences in the axis observed in hearts from small versus large species affect the properties of the dual pathways. The cellular composition of the fast and slow pathways is similarly unclear, as is the determinant of the functional difference between the dual wavefronts. The answers to these and many other questions require further combined morphological-electrophysiological investigations.

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