Electrophysiological Determinants of Antidromic Reentry Induced During Atrial Extrastimulation

Insights From a Pacing Model of Wolff-Parkinson-White Syndrome

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The electrophysiology of antidromic reentry, a less common phenomenon than orthodromic reentry, remains a poorly understood aspect of the Wolff-Parkinson-White (WPW) syndrome. We used a pacing model of ventricular preexcitation in patients without WPW, so that electrophysiological events in the normal pathway during atrial extrastimulation (A1-A2 technique) could be precisely delineated without the obscuring effect of an actual accessory pathway. Ventricular preexcitation was simulated by an A1-V1 sequential basic drive with A2-V2 extrastimulation at progressively shorter A1-A2 (equal to V1-V2) coupling intervals. At each coupling interval tested within the zone of atrioventricular (A-V) nodal effective refractory period (since anterograde block of A2 was considered mandatory for manifestation of antidromic reentry), responses were assessed after A2 alone (method I), V2 alone (method II), and A2 plus V2 (method III, the complete preexcitation model). The entire pacing protocol was performed at two A-V intervals, short (50 msec) and long (150-180 msec), thereby simulating different proximities between the A pacing site and "accessory pathway" location. Of 47 consecutive unmedicated patients screened for the study protocol, 38 failed to meet minimal prerequisites for possible initiation of antidromic reentry because of failure in 18 (38% of total) to achieve anterograde A-V nodal block of A2, even though 1:1 ventriculoatrial conduction to cycle lengths less than or equal to 500 msec (<400 msec in 12) was present; and poor or absent ventriculoatrial conduction in the others. The nine remaining candidates underwent the full pacing protocol. Antidromic reentry (retrograde atrial response following V2 in method III) was observed in only two cases (4% of total), and both were associated with retrograde His-Purkinje system delays (documented by method II) occurring in tandem with a long A-V interval, thereby allowing for completion of retrograde A-V nodal recovery after penetration by A2. Indeed, such a prolonged recovery time prevented initiation of antidromic reentry in six of the nine patients (proven by intact ventriculoatrial conduction in method II). Retrograde A-V nodal block of V2, independent of A2, prevented an antidromic echo in one case. Findings in our model help to clarify the various factors, including specific anterograde and retrograde A-V nodal properties; anatomic relation between the accessory and normal pathways; and the retrograde His-Purkinje system delays, that must prevail in a concerted fashion to permit the initiation of antidromic reentry during the A1-A2 technique in patients with the WPW syndrome. (Circulation Research 1989;65:295-306)
well understood, although impaired retrograde conducting capability of the normal pathway has been invoked. While such an explanation might be applicable in some cases, it does not suffice for elucidating the rarity of antidromic reentry initiation in the majority of patients who should have intact and, in many cases, excellent retrograde conduction. Insight into the latter problem can be achieved only by quantitatively characterizing the various electrophysiological prerequisites within the A-V node and His-Purkinje system (HPS) that must be satisfied to permit occurrence of the very first antidromic echo during attempted tachycardia induction. It would be ideal to obtain these data from patients with the WPW syndrome who undergo electrophysiological testing. Unfortunately, the very presence of an accessory pathway (AP) severely hampers such an effort owing to the obscuring effect of ventricular preexcitation on events occurring in the anterograde direction within the normal pathway during programmed stimulation. Even an accurate assessment of retrograde A-V nodal-HPS conduction is often not feasible in the setting of retrograde atrial activation via the AP.

To circumvent these methodological obstacles, we constructed a pacing model of the WPW syndrome in patients lacking APs. This model enabled us to analyze electrophysiological events occurring during attempted induction of an antidromic echo by a single atrial extrastimulus in the presence and absence of a simulated bypass tract. Our findings shed new light on what is currently a poorly understood aspect of the WPW syndrome.

**Subjects and Methods**

For inclusion, patients had to be in normal sinus rhythm, have normal A-V node and HPS function, lack both APs and A-V nodal reentry, and lack inducible sustained atrial tachyarrhythmias.

Forty-seven consecutive patients undergoing intracardiac electrophysiological evaluation for a variety of clinical indications met these inclusion criteria. Although the primary reasons for the studies were clinical indications, the experimental nature of the pacing protocol described later was explained to the patients, and signed consents were obtained. Antiarrhythmic medications were discontinued for at least five half-lives beforehand.

In each case, standard intracardiac recording and stimulation methods were used. Additionally, the following pacing model of ventricular preexcitation was used: Figure 1 schematically depicts each component of the pacing model by a ladder diagram in which sequential electrical stimuli introduced in the right atrium and right ventricle subsequently invade the normal pathway during programmed stimulation. During the basic A1 drive, each corresponding V1 simulates ventricular preexcitation resulting from anterograde propagation of the A1 impulse over a hypothetical bypass tract. Thus, the A1-V1 interval may be taken to represent atrial-to-delta interval. Please note that throughout this paper, for purposes of clarity, the designations A1, V1, A2, and V2 are used in place of the stimuli that give rise to them. Such substitutions are valid because coupling intervals with increased stimulus-to-response latency were excluded from analysis.

In all three methods, the A1-A2 cycle length is constant, and the A2-V1 intervals are identical. However, in method I (Figure 1), an atrial extrastimulus alone (A2) is introduced at the longest coupling interval associated with anterograde block in the conduction system, localized to the A-V node in this series. The A1-A2 cycle length is constant, and the A2-V1 intervals are identical. However, in method I, an atrial extrastimulus alone (A2) is introduced at the longest coupling interval associated with anterograde block in the conduction system, localized to the A-V node in this series.
Method II is then used to give insight into the electrophysiological fate of the solitary preexcited ventricular impulse (V2) associated with A2 (Figure 1). Although A2 is omitted, V2 is introduced at an interval after V1 that is identical to the A1-A2 coupling interval of method I. The designations “H1” and “A1,” respectively, represent retrograde activation of the His bundle and atria by the V2 impulse.

Methods I and II are then “combined” in method III to form the complete model (Figure 1). Since in manifest preexcitation the V1-V2 interval is expected to equal A1-A2, the A-V interval during extrastimulation is identical to that of the basic drive. Antidromic reentry during method III, were it to occur, would be indicated by retrograde capture of the atria by the V2 impulse. The basic cycle length used in the pacing model is the longest multiple of 50 msec associated with demonstrable anterograde block of A2, without impinging on the relative refractoriness of the atrium. In all of the pacing methods, the A1-A2 and V1-V2 coupling intervals are progressively shortened in tandem until the functional refractory period of either the atrium or ventricle is achieved. Thus, the pacing model assumes that the electrophysiological prerequisite of a short AP effective refractory period (ERP) is satisfied. This is an essential characteristic of the model since antidromic reentry is unlikely to be associated with a long anterograde ERP-AP.

When antidromic reentry did not occur despite intact ventriculoatrial conduction associated with V2 in method II, the retrograde A-V nodal recovery time after antegrade penetration by A2 was assessed with method IV (Figure 1). In this method, A2 is held fixed at, or just within, the A-V nodal ERP. V2 is then introduced at progressively longer A2-V2 intervals to determine when V2-A2 conduction will return.

Ordinarily, in patients with WPW syndrome, the atrial-to-delta interval during atrial pacing is largely a function of the distance between atrial pacing site and the bypass tract and conduction time within the AP. To take these variables into account in our model, the entire pacing protocol was performed both at an A-V interval of 50 msec, which is usually associated with intranodal collision, and at a longer interval of 150–180 msec, intended to produce impulse collision in the HPS. This span of A-V intervals closely approximates the actual full range of stimulus-to-delta intervals that have been reported during atrial pacing in patients with APs.6-9

Definitions

Programmed A-V intervals. The A1-V1, and A2-V2 intervals programmed during the screening of all basic cycle lengths tested. These measurements were made from the stimulus artifact and remained fixed in given patients during methods I through III.

Zone of A2 block (in method I). Range of coupling intervals extending from the A-V nodal ERP to the functional refractory period of the atrium.

Relative refractory period of the His-Purkinje system (in method II): Defined as the longest V1-V2 interval associated with emergence of retrograde His bundle potential (H1) from the local V2 electrogram.

A2-H2 interval (in method III). The interval from the onset of atrial deflection (A2) on the His-bundle electrogram to the onset of retrograde His bundle deflection (H2) in the event the latter emerged from the V2 electrogram. This interval provided some estimate of the time elapsed between antegrade A-V nodal penetration by A2 and approach of the subsequent V2 impulse at the level of the A-V node.

Recovery interval (A1-V2, in method IV). When an antidromic echo could not be elicited with method III, the A2-V2 was progressively prolonged as pointed out above. The recovery interval was defined as the shortest A2-V2 (longer than A1-V1) that resulted in V2 being able to conduct to the atria (A1). Method IV was obviously not tested when an antidromic echo was observed with method III.

Results

Before performance of the complete pacing protocol described above (Figure 1), 47 consecutive patients were evaluated for their ability to satisfy minimum electrophysiological prerequisites for manifestation of antidromic reentry with atrial extra stimulus technique. These included 1) anterograde block of A2 in the A-V conduction system (always localized to the A-V node in this series) during atrial extrastimulation with method I, using at least one basic A1-V1-A2-V1 cycle length (i.e., down to either 400 msec or a value within 50 msec of the shortest cycle length associated with 1:1 A-V nodal conduction, whichever was shorter). For this purpose, extrastimulation was performed only at a long A-V interval, as intranodal collision at an A-V of 50 msec could only have shortened A-V nodal refractoriness; 2) ability of the A-V node to conduct retrogradely in a 1:1 fashion to cycle lengths less than or equal to 500 msec during incremental ventricular pacing because antidromic tachycardias with longer cycle lengths are not likely to be clinically significant and have seldom been reported; 3) short anterograde AP refractoriness. This prerequisite could be satisfied in all patients because simulated anterograde AP conduction down to short coupling intervals could be programmed in our model and was limited only by atrial and/or ventricular muscle refractoriness.

Of the 47 patients evaluated, 38 failed to meet these elemental electrophysiological prerequisites. The distribution of conduction characteristics in these 38 cases (22 men and 16 women, mean age 56 years) is shown in Figure 2. Failure to achieve anterograde block of A2 made initiation of antidromic reentry impossible in 18 patients with 1:1 retrograde conduction to cycle lengths less than or equal to 500 msec (12 of whom had 1:1 ventriculoatrial conduction to cycle lengths ≤400 msec). In contrast, the shortest atrial cycle associated with 1:1 antero-
A2 could not be achieved. When atrioventricular nodal conduction was good and would allow antidromic reentry, an anterograde block of effective refractory period (ERP-A VN) was encountered (unfilled area), the retrograde conduction characteristics were such that antidromic reentry would not be likely.

Figure 2. Frequent failure to satisfy minimal prerequisites for antidromic reentry. Graph depicts distribution of anterograde and retrograde parameters in 38 patients scanned for possible inclusion in this study but who did not qualify. When retrograde conduction was good and would have allowed antidromic reentry, an anterograde block of A2 could not be achieved. When atrioventricular nodal effective refractory period (ERP-AVN) was encountered (unfilled area), the retrograde conduction characteristics were such that antidromic reentry would not be likely.

Table 1. Baseline Clinical and Electrophysiological Data

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All values except age in milliseconds.

OHD, organic heart disease; SCL, sinus cycle length; Ant. cond., anterograde condition; Ret. Cond., retrograde condition; F, female; M, male; ASHD, atherosclerotic heart disease; VT, ventricular tachycardia; VF, ventricular fibrillation; sust., sustained; DCM, dilated cardiomyopathy; NS, nonsustained.

Programmed A-V Delays and Site of Collision

At the basic cycle lengths used, all patients had intact A-V and V-A conduction and, therefore, a collision of the anterograde and retrograde impulses along the A-V node—HPS must have taken place during the basic drive. Since the retrograde HPS conduction times (V1-H1 intervals) during ventricular pacing at least equal sinus H-V intervals, it is clear that the impulses collided in the HPS at the long programmed A-V intervals (Figure 3, all panels) in each patient at the basic cycle lengths tested. This could also be directly documented in every instance since the anterograde H1 could be identified during the basic A2-H1 drive in each case (Figure 3). With the short A-V delay (50 msec), the V1 stimulus preceded the anticipated anterograde H1 by a minimum of 100 msec except in patient 1, where the value was 75 msec. These measurements exceeded corresponding H-V intervals by at least 35 msec (range 35–95 msec; mean 67±21 msec). Hence, it seems logical to assume that at shorter programmed A-V delays, the collision of the two impulses occurred in the A-V node (Figure 4, all panels). As would be expected, the anterograde His-bundle deflection could not be identified at these short A-V delays.

Basic Cycle Length and the Zone of A2 Block (Method I)

Since block of A2 in the A-V node was considered a prerequisite for full testing with the pacing model, Table 2 depicts the longest basic cycle length in individual patients where this could be accomplished. To achieve A-V nodal block of A2, it was necessary to scan relatively short basic cycle lengths, that is, less than or equal to 550 msec in five of nine patients. A-V nodal ERP was encountered in all patients at the long programmed A-V intervals (Figure 3D) although the zone of block was usually quite narrow, as can be appreciated in Table 2. At the shorter programmed A-V delays, the A2 did not block in the A-V node in three of nine patients.
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<th>Ret. RRP-HPS*</th>
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| All values measured in milliseconds. Plus and minus signs reflect the presence or absence of a given event, respectively. HBE, measurement made on His bundle electrogram; RRP-HPS, relative refractory period-His-Purkinje system; ERP-AVN, effective refractory period atrioventricular node; FRP-At, functional refractory period-atrium. *< Implies values less than the functional refractory period of ventricular muscle. **Atrioventricular nodal penetration did not occur due to retrograde block in the HPS.
FIGURE 3. Responses to A1 and V2 at long atrioventricular (AV) delays (Patient 9). Tracings shown here and in Figure 4 represent typical responses using the pacing protocol depicted in Figure 1. Each panel represents from top to bottom surface ECG lead V5, His bundle (HB), and right bundle (RB) electrograms. Atrial stimulation is depicted with white arrows, and ventricular stimulation is represented by black arrows. S1, A1, H1, and V1 stand for stimulus artifact, atrial, His bundle, and ventricular electrograms of the basic drive beat. S2, A2, and V2 represent responses during the premature beat. The retrograde His bundle and atrial deflections in response to V2 are labeled Hr and Ar, respectively. The anterograde counterpart is labeled H2. In all panels, at a basic cycle length (BCL) of 700 msec and AV interval of 150 msec, the anterograde His-bundle deflection (H2) can be identified and, therefore, the collision of A1 and V1 occurs below the AV node. At a H2 of 360 msec, whereas A2 blocks in the AV node at an A2-H2 of 290 (D; method I of pacing protocol). At corresponding intervals, the V2 alone (method II) is delivered in B and E, respectively. Although in both instances the V2 impulse reaches the atria (Ar), the emergent Hr and RB deflections can be clearly identified in E due to shorter V1-V2 of 290 msec. When both A1 and V2 are delivered with A1-A2 of 150 (the same as A2-V2) in C and F (i.e., method III), an Ar response occurs in F (antidromic echo) but not in C since the V2 impulse collides with oncoming A2 impulse in the AV node as suggested by the emergent RB deflection in response to V2 (which can be identified at the tail end of V2 in B and C). Note that concealed intranodal penetration by the blocked A2 results in prolonged H2-A2 conduction time of 200 msec in F vs. 85 msec in E. Because the Hr and RB deflections show identical timing with or without A2 in F and E, respectively, these can be confidently labeled as responses to V2 and not A2.

Response to V2 Without Antecedent A1 (Method II)

Successful propagation of V2 to atria (A1) occurred in all patients throughout most of the scanning (Figures 3E and 5D). Retrograde His deflection (H1) emerged from V2 (HPS-relative refractory period) in four patients (1, 2, 8, and 9) and, at comparable V1-V2, greater HPS delays (V2-H1) were observed with shorter programmed A-V intervals in keeping with the known abbreviation of HPS refractoriness with intra HPS collision seen at longer A-V delays.11 The V1 impulse was associated with retrograde block in the HPS at certain coupling intervals but only at shorter A-V delays in two patients (2 and 9, Figure 4H) and in the AV node in only one patient (4) at both A-V delays (Figure 6).12 In the absence of an identifiable H1 deflection, the site of block was documented with the use of an atrial “probe” for

(patients 5–7), and the ERP-AV node was less than the atrial functional refractory period. However, in the remaining six patients, A1 blocked in the A-V node at shorter A-V delays as well (Figure 4G).

Response to V2 Without Antecedent A1 (Method II)
detecting prior concealment in the A-V node (Figure 6). It could therefore be deduced that without antecedent A2, the V2 would be expected to produce an A2 response in most instances (i.e., except patient 4 and at certain coupling intervals in patient 9).

Responses to V2 With Antecedent A2 (Method III, the Complete Preexcitation Model)

As can be appreciated in Table 2, the V2 impulse did not reach the atria when preceded by A2 in seven of nine patients (1-7) (Figure 5). In only two patients (8 and 9), and only at the longer A-V delays, was a retrograde A2 response produced (antidromic echo) (Figure 3F). Inasmuch as retrograde HPS conduction was not a limiting factor for V2 propagation to the atria without preceding A2 (proven by method II), it is logical to assume that with method III, the V2 impulse reached the A-V node but did not successfully traverse that structure. In two patients (2 and 9), however, at shorter A-V delay and at certain V1-V2 intervals, the V2 did block in the HPS during methods II and III (Figures 4H and 4I).

Maximum A2-H2 Intervals

Since the retrograde His deflection emerged in only four patients (1, 2, 8, and 9), the A2-H2 values could not be measured in the remaining cases. A given value of A2-H2 interval (equal to A2-V2+V2-H2)
FIGURE 5. Delayed atrioventricular (AV) nodal recovery time as the main impediment to antidromic reentry (Patient 7).
Tracings from top to bottom are ECG lead V1, coronary sinus (CS), and His bundle electrograms. A: Block of A2 in the AV node at an A1-A2 of 270 msec (method I). B: V2 conducts to the atria (A). No retrograde His-Purkinje system (HPS) delays can be appreciated since no Hr can be identified (method II). C: Combined A1-V2 (complete preexcitation model, method III) is not followed by an A2 suggesting a block of V2 in the AV node. D and E show (with method IV) that after a block of A2 in the AV node, an A1-V2 interval of 330 msec (E) is required for the V2 impulse to reach the atria. It is clear, therefore, that the programmed A1-V2 150 msec is much too short for antidromic reentry to occur. BCL, basic cycle length.

was a function of its two component factors, having opposite effects on the A2-Hr values at the two sets of A-V intervals used during this study. At short A-V delays, the V2-Hr intervals were longer at comparable V1-V2. Due to a decrease of 100 msec or greater in the A-V interval at shorter A-V delays (compared with the longer A-V intervals), however, the net effect on A2-Hr interval varied (Table 2). The longest values (i.e., >200 msec) were seen in two cases (patients 8 and 9) at the longer A-V delays.

Antidromic Echo Beats

Antidromic echo beats occurred in only two patients (8 and 9) and only at longer A-V delays (Figure 3F). It is of interest to note that these patients showed the longest A2-Hr intervals recorded in this study. Antidromic reentry was not seen in any of the patients where the retrograde His bundle did not emerge from the V2 electrogram. As would be expected, in some of the cases in this series was an antidromic echo seen during the basic (A1-V1) drive.

A-V Nodal Recovery Interval (A1-V2, Method IV)

Since it could be determined that the A-V node posed the main obstacle for the occurrence of antidromic reentry, the A2-V2 intervals were progressively increased in six of nine patients (1-3 and 5-7) to determine retrograde A-V nodal recovery after A2 block (method IV, Figures 1 and 5). These values exceeded the longer programmed A-V delays by at least 10 msec in three cases and by at least 80 msec in another three cases. In one patient (4), the recovery values were not tested since the V2 demonstrated a retrograde block in the A-V node even without preceding A2 (Figure 6).

Discussion

The findings of this study provide significant new insight toward our understanding of the electrophysiological substrate required for the initiation of antidromic reentry. The practical value of the model is obvious since this type of information cannot be
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 gathered from the study of patients with WPW syndrome. Before discussing the electrophysiological data in detail, it is worthwhile to examine the validity of the model.

The key advantage of the pacing model is the ability to isolate the responses of the normal pathway (i.e., the A-V node and HPS) to atrial versus preexcited ventricular impulses by individual programming of $A_2$, $V_2$, or both. In patients with manifest preexcitation, the very presence of A-V conduction over the AP during atrial pacing renders dissection of subsequent events into anterograde versus retrograde components impossible with each $A_2$ (Figures 3 and 4). The second important advantage of the model is the knowledge of collision site (i.e., A-V node or HPS) between the atrial and ventricular wave fronts. Since spontaneous preexcitation does indeed represent sequential atrial and ventricular impulse input with a constant A-V delay (by way of the AP), the model represents a fairly accurate replication of the real situation. However, the advantage of the model is that one can study the effect of both intranodal as well as HPS collision, whereas during spontaneous preexcitation, the level of collision cannot be accurately determined during full preexcitation that occurs with increasing paced atrial rates and when maximum preexcitation is present during sinus rhythm.

The obvious disadvantage of the model is that the response to artificial preexcitation (i.e., ventricular pacing) could differ fundamentally in some ways from preexcitation secondary to conduction over an AP. Although this hypothetical problem cannot be discounted, there is no apparent reason to believe that such differences indeed exist. The second potential problem is whether a single ventricular pacing site such as right ventricular apex or outflow tract is representative of other AP locations. Although right ventricular pacing (apical or outflow) would be considered closer to anteroseptal and to some extent posteroseptal locations, other sites are well represented in the model by virtue of the longer preselected A-V delays of 150–180 msec in this series. In antidromic reentry, the site of other AP locations, such as right or left free wall, is only relevant to the extent these pathways are remote from the A-V
junction and consequently the normal pathway. From those locations, therefore, the invasion of ventricular impulse into the normal pathways is delayed. This physiological condition was simulated by programming longer A-V delays in our model. Perhaps the only concern of real consequence is whether the anterograde and retrograde electrophysiological properties of the A-V node and HPS in patients with WPW syndrome are in any way different from those lacking ventricular preexcitation. Our own observations along these lines suggest that the normal pathway properties in patients with WPW syndrome are virtually identical to those without, in a nonmedicated postabsorptive state (authors' unpublished observations). On the basis of the above considerations, it seems logical to assume that extrapolations from the findings of this study to antidromic reentry should be valid for the most part.

The data presented here suggest that true antidromic reentry (i.e., retrograde conduction via the normal pathway) during atrial extrastimulation would be relatively rare (i.e., two of 47, or <5%), which is strikingly in line with clinical observations. This low figure is derived from the screening of consecutive patients tested to assess suitability for possible occurrence of antidromic reentry using the pacing model. Since the mean age of these cases was higher than the average age of patients who have symptomatic tachycardias in association with WPW syndrome, the projected figure may be an underestimation if conduction characteristics of the normal pathway are markedly different at a somewhat younger age. However, even in those cases selected to be ideally suited for antidromic reentry, only a minority showed the actual reentry, (two of nine or 22%). It must be emphasized that poor retrograde A-V nodal conduction, per se, is inadequate to account for the low occurrence of antidromic reentry since 1:1 ventriculoatrial conduction was present to a cycle length of less than or equal to 500 msec in 27 of 47 (57%) patients screened. Our study of the pacing model reveals that there are a variety of parameters that influence the occurrence of manifest antidromic reentry, and these will now be discussed in greater detail below.

Determinants of Antidromic Reentry

The main factors that would facilitate antidromic reentry after A2 include 1) a relatively proximal block in the normal pathway, preferably proximal A-V node. In this context, it should be noted that in the 47 consecutive patients screened, the A-V nodal ERP was not encountered in 18 of 38 during the A1-A2 technique. If antidromic reentry does not occur despite block of A2 in the A-V node, it is highly unlikely that this phenomenon will be associated with the block of A2 more distally, that is, in the HPS or if A2 fails to block (Figures 3 and 4). 2) A-V nodal recovery after anterograde block of A2, for subsequent retrograde propagation of the ventricular impulse generated by the AP (or paced impulse) reaching the A-V node through the HPS. The likelihood of effective retrograde propagation will be naturally enhanced by delayed arrival of such an impulse at the level of the A-V node, which in turn could be made possible by two factors: a) a longer distance to site of the AP (simulated by long programmed A-V delay) and b) retrograde delays in the HPS. The interplay of the various anterograde and retrograde conduction parameters deducible from the results of this study could be quite complex and are detailed as follows:

I. Anterograde block in the A-V node. It is apparent that in the absence of intranodal block of A2, antidromic reentry is less likely. Therefore, factors that shorten the A-V nodal ERP, such as intranodal collision of atrial and ventricular impulses, could reduce the chances of antidromic reentry. It is for these reasons that relatively short cycle lengths had to be scanned in many of the cases and that antidromic reentry was noted only at the longer A-V intervals where the site of collision was below the level of the His bundle, thereby avoiding a shortening of A-V nodal ERP, which may occur with intranodal collision.

The achievement of anterograde block of A2 in the A-V node does not necessarily guarantee that antidromic reentry will ensue even if the retrograde conduction characteristics would allow it, since in seven of nine such cases (78%), reentry was not seen. The possibility exists that shorter A1-A2 would result in more proximal block in the A-V node. However, from the narrow range of A1-A2 intervals (noted in this study) where A-V nodal ERP was encountered without encroaching on the atrial relative refractory period, it seems that such flexibility is uncommon. It is, nonetheless, quite possible that the intranodal site of block may have to be more proximal to hasten A-V nodal recovery. This element of A-V nodal physiology is not clearly understood and certainly cannot be proven from this study. It is not unreasonable to speculate, however, that antidromic reentry will not take place if A2 impulse managed to reach the His bundle (Figures 3 and 4).

II. Programmed A-V delays (role of the P-R interval). Because most patients with WPW syndrome exhibit ventricular preexcitation with a visible anterograde His-bundle activation during sinus rhythm, the fusion of the atrial and ventricular impulses occurs more distally. The collision sites of these wave fronts in the two ventricles vary, however, in that the impulses are more likely to collide in the HPS in the ventricle ipsilateral to AP location (or ventricular pacing site) and in the myocardium of the contralateral ventricle. However, with shorter paced basic atrial cycle lengths, the collision sites will be progressively more proximal along the A-V node-HPS axis due to a fixed A-V interval but slower anterograde A-V nodal conduction. Intranodal collision is quite likely during full preexcita-
tion as a result of 1) shortened basic cycle length and consequent conduction delays in the A-V node or 2) earlier entry of atrial impulse into the ventricle (relative to the normal pathway) via an AP (proximity of and/or rapid conduction in AP or slow conduction in the normal pathway). Therefore, the A-V delays chosen in this study are quite representative of the ranges seen in patients with WPW syndrome and certainly span the physiological spectrum of associated collision sites.

As one would predict, longer A-V delays will favor the occurrence of antidromic reentry by a combined effect of 1) preventing the shortening of A-V nodal refractoriness due to infranodal collision and 2) delaying retrograde input into the A-V node. It is interesting to note that in the two patients who demonstrated manifest antidromic reentry, the phenomenon indeed occurred at the longer A-V delays.

III. Retrograde delays in the HPS. As mentioned above, the occurrence of retrograde delays in the HPS will provide additional time for the A-V node to recover after concealed infranodal penetration by A2. Since atrial pacing in WPW syndrome essentially constitutes A-V sequential pacing during the basic drive and the atrial premature beat, the occurrence of functional retrograde block in the HPS is not unexpected after the extrastimulus. However, the magnitude of such delays depends on several factors including the basic cycle length, site of collision of atrial and ventricular impulses, and the prematurity of the stimulus. The effect of cycle length on HPS refractoriness is well known, and greater delays are seen at longer cycles. In only one of five patients, the retrograde His deflection emerged from V2 in this study when the basic cycle length measured less than or equal to 550 msec. Longer A-V delays result in infranodal collision, which would tend to shorten HPS refractoriness. Progressively closer coupled extrastimuli would cause further delays in the HPS, and it would seem, therefore, that antidromic reentry is more likely to be induced at shorter coupling intervals.

A number of published examples of antidromic tachycardia initiated by atrial pacing indeed demonstrate the occurrence of functional retrograde HPS delays at tachycardia onset. However, the attainment of retrograde HPS delays alone may not be sufficient to result in antidromic reentry. Minimum requisite retrograde delays must be "reference" to prior anterograde A-V nodal penetration and, hence, the magnitude of A2-H1 intervals (composed of A2-V2 plus V2-H1). Interestingly, in our study, the A2-H1 intervals were indeed longest in the patients who manifested antidromic reentry. In this context, it is pertinent to point out that the presence of a preexisting (as opposed to functional) retrograde bundle branch block ipsilateral to the AP should also increase the likelihood of antidromic reentry.

Electrophysiological and Clinical Implications

It is readily apparent that the type of information gathered from the present study, even though quite germane to antidromic reentry, has not heretofore been available from the investigations of patients with manifest ventricular preexcitation, including those with antidromic tachycardia. Our study illustrates that the main impediments to antidromic reentry include short anterograde A-V nodal refractoriness, close location of the AP to the A-V junction (i.e., paraseptal pathways), and lack of retrograde HPS delays, as well as typically prolonged retrograde A-V nodal recovery time following anterograde concealment by A2 and/or diminished intrinsic retrograde A-V nodal conduction capability. Conversely, certain electrophysiological parameters may facilitate initiation of antidromic reentry, namely proximal anterograde intranodal block, longer A-V delays, and retrograde functional delays in the HPS. Elucidation of factors that promote the occurrence of antidromic reentry should help to better understand this entity in patients with WPW syndrome.

As a starting point, one can more clearly see why this type of reentry is uncommon during atrial extrastimulation. A combination of long anterograde A-V nodal ERP, good retrograde conduction, and a quick recovery of excitability in the same tissue may be hard to achieve. Furthermore, factors that promote intranodal block of A2 (e.g., short cycle length) also limit maximum achievable HPS delays, which seem to be important for initiation of antidromic reentry. It would not be unreasonable to postulate that, in patients with WPW syndrome, the initiation of preexcited circus movement tachycardia without a discernible retrograde His-bundle potential at the tachycardia onset should raise the possibility of another AP comprising the retrograde limb or A-V nodal reentry with bystander AP conduction. One can further postulate that antidromic tachycardia using an anteroseptal or posteroseptal AP would be exceptionally rare. Although thoughts along these lines have been expressed previously, the present study is the first to provide a sound electrophysiological basis for the observed phenomena.

In the same light, the findings suggest that the occurrence of double ventricular responses after a single A2 could be ascribed to a variety of mechanisms. Although the origin of second ventricular response from anterograde conduction versus reentry within the HPS could be ascertained in this study (e.g., Figure 4), it cannot be definitively determined in patients with spontaneous preexcitation. The only alternative approach to making such a distinction would be to use additional recordings from the bundle branches. In the absence of such recordings, interpretations concerning the origin of double ventricular responses in patients with WPW syndrome are open to serious questions.

Limitations of the Study

The model used in this study only examines the electrophysiological impediments and facilitating parameters if antidromic reentry initiation is
attempted using a single atrial extrastimulus. Although the onset of antidromic reentry with rapid atrial pacing was not tested here, it is conceivable that some of the same factors could be involved (except for more readily achievable A-V nodal block), but this cannot be stated with certainty. In the event that a ventricular extrastimulus initiates antidromic reentry, also not studied in our model, a different set of circumstances will be needed, such as long retrograde ERP-AP (in association with moderate to short anterograde ERP-AP) and a long ventriculoatrial interval via the normal pathway. These prerequisites may not be easily satisfied, although published examples suggest here too the important role of retrograde HPS delays (providing adequate V-A prolongation) for initiation of antidromic reentry.9,17,18

Another obvious limitation is that while the model addresses creation of the first antidromic echo, it does not speak to the factors essential for sustenance of such a tachycardia. Even though not studied, one can state that sustained antidromic reentry will be relatively rarer since some of the individuals demonstrating a single antidromic echo may not be able to perpetuate the process. The understanding of factors that would facilitate the occurrence of sustained antidromic reentry is obviously important but, again, will likely require the study of a model such as presented here, since such data would be difficult to obtain in patients with WPW syndrome.

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