JACC Vol. 5, No. 4
April 1985:898–903

METHODS

Electrophysiologic Demonstration of Concealed Conduction in Anomalous Atrioventricular Bypass Tracts

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To demonstrate the occurrence of concealed conduction in anomalous atrioventricular (AV) bypass tracts, 11 patients were selected for study. Two had a right-sided and nine had a left-sided bypass tract. Electrode catheters were placed in the right atrium, coronary sinus, AV junction and right ventricle. After every eighth atrial or ventricular driving beat (A_1 or V_1) at a constant cycle length, two successive atrial or ventricular premature beats (A_2 and A_3 or V_2 and V_3) were delivered. The A_1A_2 or V_1V_2 interval was fixed at 30 ms greater than the effective refractory period of the atrium or right ventricle, but less than the effective refractory period of the bypass tract in the anterograde or retrograde direction. This allows A_2 or V_2 to capture the atrium or ventricle, but not conduct in the bypass tract. The A_3 or V_3 was delivered from late diastole with a progressively shorter A_2A_3 or V_2V_3 interval until atrial or ventricular refractoriness was encountered.

In the anterograde direction, the presence of A_2 prevented A_3 conduction in the bypass tract despite A_1A_3 intervals being longer than the anterograde effective refractory period of the bypass tract in 8 of the 11 patients. In the retrograde direction, the presence of V_2 prevented V_3 conduction in the bypass tract despite V_1V_3 intervals being longer than the retrograde effective refractory period of the bypass tract in 3 of the 11 patients. Thus, using the technique of programmed electrical stimulation, concealed conduction in anomalous AV bypass tracts can be demonstrated in both anterograde and retrograde directions.

(J Am Coll Cardiol 1985;5:898–903)

Concealed conduction occurs when a nonpropagated impulse influences the conduction of a subsequent impulse (1). This electrophysiologic phenomenon has been validated in animal experiments with programmed electrical stimulation and microelectrode recording from various levels of the atrioventricular (AV) system (2–4). In the human heart, concealed conduction has been demonstrated in the AV node, His-Purkinje system and atrium (5–9).

Concealed conduction in anomalous AV bypass tracts has been postulated (10–13) and may be an important factor in determining the ventricular response during atrial flutter-fibrillation in the Wolff-Parkinson-White syndrome (14,15). This electrophysiologic phenomenon has not been systematically studied previously. The purpose of this study is to document the occurrence of concealed conduction in anomalous AV bypass tracts using the techniques of intracardiac recording and programmed electrical stimulation.

Methods

Patients. Evidence of concealed anomalous AV bypass tract conduction was obtained in 11 patients undergoing cardiac electrophysiologic studies for the evaluation of symptomatic manifest or concealed Wolff-Parkinson-White syndrome (16). Their clinical data are presented in Table 1. Of the 11 patients, there were 8 men and 3 women whose ages ranged from 20 to 62 years. All patients had symptomatic AV reciprocating tachycardia. Three patients (Cases 1, 4 and 10) also had atrial fibrillation.

Electrophysiologic study. Informed written consent was obtained from each patient and all cardiotonic and antiarrhythmic agents were discontinued for at least 72 hours

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0735-1097/85/$3.30

Table 1. Clinical Profile of 11 Patients

Case	Age (yr) & Sex	Clinical Arrhythmias	Location of AP
1	38M	PSVT, AF	L
2	36F	PSVT	L
3	52F	PSVT	R*
4	27M	PSVT, AF	L
5	40M	PSVT	L
6	29M	PSVT	L*
7	47F	PSVT	R
8	46M	PSVT	L
9	62M	PSVT	L
10	20M	PSVT, AF	L
11	30M	PSVT	L

*Capable only of retrograde conduction. AF = atrial fibrillation; AP = anomalous pathway; F = female; L = left-sided; M = male; PSVT = paroxysmal supraventricular tachycardia; R = right-sided.

before the study. The study was performed in a postabsorptive state. His bundle and low septal right atrial electrograms were recorded with a quadripolar electrode catheter positioned across the tricuspid valve. Additional quadripolar electrode catheters were positioned in the high right atrium, coronary sinus and right ventricular apex for pacing and recording of right atrial, left atrial and right ventricular electrograms. All intracardiac electrograms were recorded at filter frequencies of 30 to 500 Hz along with surface electrocardiographic leads I, II and V_1 on a multichannel oscilloscopic photographic recorder at a paper speed of 100 mm/s. Electrical stimulation was performed with a programmed digital stimulator (Bloom & Associates) delivering impulses 2 ms in duration at a current twice the diastolic threshold (12).

The double extrastimuli ($S_1S_2S_3$) method (Fig. 1) was used for testing the occurrence of concealed bypass tract conduction. In the anterograde direction, right atrial stimulation was performed if the anomalous AV bypass tract was right-sided, and coronary sinus stimulation was performed if it was left-sided. In the retrograde direction, ventricular stimulation was performed only at the right ventricular apex. After every eighth basic driving beat (S_1), premature stimuli (S_2 and S_3) were delivered. The S_1S_2 interval was set at 30 ms greater than the effective refractory period of the paced site, but less than the effective refractory period of the bypass tract. This allowed S_2 to capture the atrium or ventricle, but not conduct in the bypass tract. A second extrastimulus (S_3) was added late in diastole and was scanned toward S_2 at 10 ms decrements (Fig. 1). If S_3 also failed to conduct in the bypass tract, S_2 was removed and stimulation was repeated with the same S_1S_3 interval. If S_3 could then conduct in the bypass tract, the previous failure of S_3 to conduct could be reasonably attributed to concealed conduction of S_2 in the anomalous AV bypass tract (1). S_2 was then reintroduced and S_3 was scanned toward S_2 until the paced tissue became refractory to S_3.

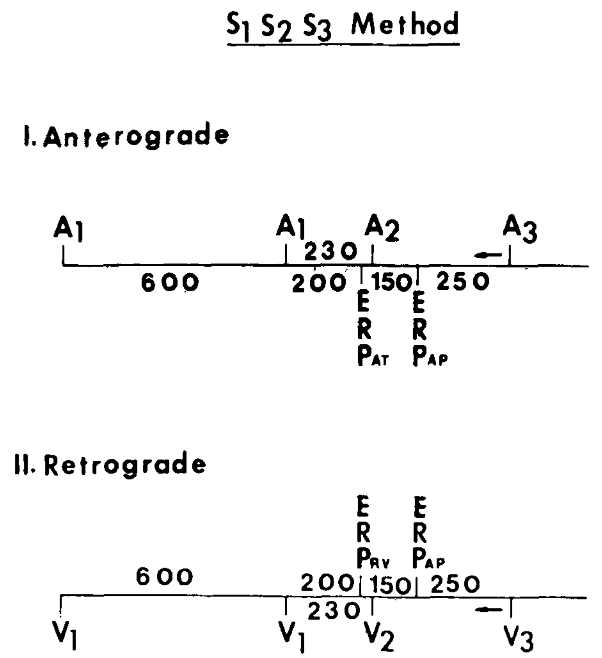

Figure 1. Illustration of the $S_1S_2S_3$ method for demonstrating concealed conduction of the anomalous atrioventricular bypass tract. **I. Anterograde**, During atrial basic drive (A_1A_1) for eight beats, the atrial premature coupling interval (A_1A_2) is fixed at 30 ms above the effective refractory period of the atrium (ERP_{AT}). A second atrial premature beat (A_3) is scanned from diastole toward A_2 at 10 ms decrements. ERP_{AP} = effective refractory period of the anomalous pathway. **II. Retrograde**, During ventricular basic drive (V_1V_1) for eight beats, the ventricular premature coupling interval (V_1V_2) is fixed at 30 ms above the effective refractory period of the right ventricle (ERP_{RV}). A second ventricular premature beat (V_3) is scanned from diastole toward V_2 at 10 ms decrements. In this and subsequent figures, A_1, A_2, A_3 and V_1, V_2, V_3 represent atrial and ventricular responses corresponding to stimuli S_1, S_2, S_3, respectively.

Because of the occurrence of latency between electrical stimulus and response of the tissue stimulated, we measured intervals of atrial and ventricular responses (A_1,A_2,A_3 and V_1,V_2,V_3) corresponding to electrical stimuli (S_1,S_2,S_3). The zone of A_2A_3 or V_2V_3 intervals was determined over which A_2 or V_2 caused conduction block of A_3 or V_3 in the anomalous AV bypass tract. The outer limit of the zone of concealed bypass tract conduction was the longest A_2A_3 or V_2V_3 interval at which A_3 or V_3 failed to conduct in the anomalous AV bypass tract. The inner limit of the zone of concealed bypass tract conduction was the shortest A_2A_3 or V_2V_3 interval that failed to conduct in the anomalous AV bypass tract. All patients tolerated the protocol well, none developed atrial flutter, atrial fibrillation or ventricular tachycardia and no complications were observed.

Results

The anomalous AV bypass tract was right-sided in two patients and left-sided in nine. In two patients (Cases 3 and

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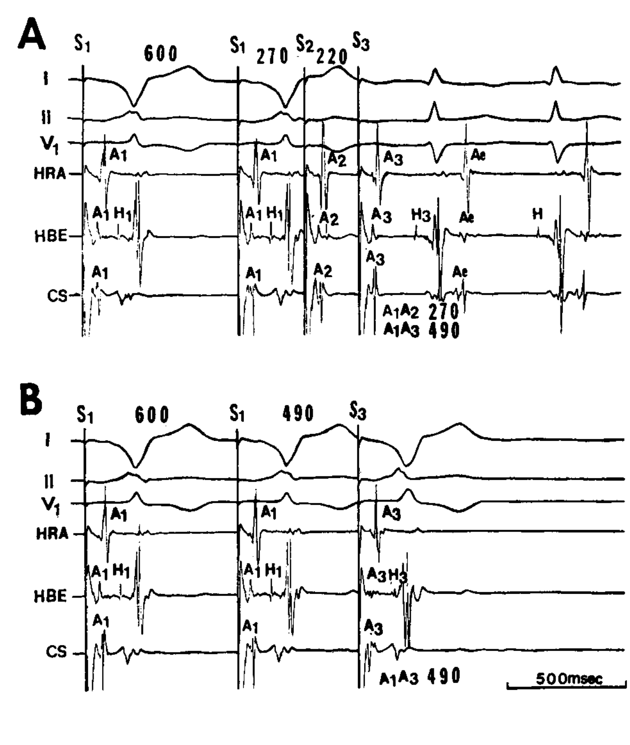
6), the anomalous AV bypass tract was capable only of retrograde conduction (16). Table 2 lists the electrophysiologic data pertaining to concealed conduction of the anomalous AV bypass tract in these patients.

Anterograde concealed conduction of the anomalous AV bypass tract (Table 2). Anterograde concealed conduction of the bypass tract was demonstrated in eight patients (Cases 1, 2, 4, 5, 7, 8, 9 and 11). The difference between the effective refractory period of the atrium and the anterograde effective refractory period of the bypass tract was 60 ms or greater in each of these patients. The width of the zones of concealed bypass tract conduction (between outer and inner limits of A_2A_3 intervals) ranged from 20 to 60 ms.

One example (Case 2) is illustrated in Figures 2 and 3. Figure 2 demonstrates the outer limit of the zone of concealed bypass tract conduction in the anterograde direction. In Figure 2A, ventricular pre-excitation through a left-sided

Figure 2. Case 2. Anterograde bypass tract concealed conduction (outer limit of the zone). **A**, Two consecutive atrial premature beats (A_2 and A_3) are blocked in a left-sided anomalous atrioventricular (AV) bypass tract during coronary sinus (CS) pacing at a basic driving cycle length (A_1A_1) of 600 ms. The A_1A_2 and A_2A_3 intervals are 270 and 220 ms, respectively. Note that A_2 is blocked in both the normal AV pathway and anomalous AV bypass tract and that A_3 is conducted over the normal AV pathway initiating an AV reciprocating tachycardia using the bypass tract for retrograde conduction. **B**, Conduction of A_3 is restored in the anomalous AV bypass tract with removal of A_2. Also note that A_3 can no longer initiate AV reciprocation. Electrocardiographic leads I, II and V_1, high right atrial electrogram (HRA), His bundle electrogram (HBE) and coronary sinus electrogram (CS) are shown. Atrial electrograms (A) and His potentials (H) are identified. Ae = atrial echo.



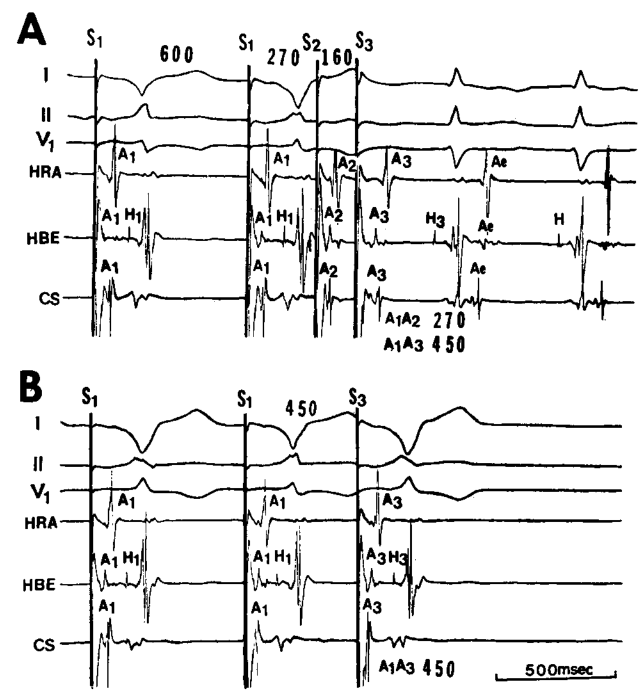


Figure 3. Case 2. Anterograde bypass tract concealed conduction (inner limit of the zone in the same patient as in Fig. 2). **A**, Compared with Figure 2, only the A_2A_3 interval has been shortened to 180 ms (corresponding S_1S_2 interval of 160 ms). A_2 and A_3 are also both blocked in the anomalous atrioventricular (AV) bypass tract. Note that A_3 is conducted over the normal AV pathway initiating an AV reciprocating tachycardia using the bypass tract for retrograde conduction. **B**, When A_2 is removed, conduction of A_3 is restored in the anomalous AV bypass tract. Also note that A_3 can no longer initiate AV reciprocation. Abbreviations as in Figure 2.

anomalous AV bypass tract is evident during pacing in the coronary sinus at a cycle length (A_1A_1) of 600 ms. The effective refractory period of the left atrium and the anterograde effective refractory period of the bypass tract are, respectively, 240 and 310 ms. The A_1A_2 interval is fixed at 270 ms. The A_2A_3 interval is 220 ms (the same as the S_2S_3 interval). Both A_2 and A_3 are blocked in the bypass tract. In Figure 2B, A_2 is removed and conduction of A_3 is restored in the bypass tract. These findings imply that A_2, which is blocked in the bypass tract, has concealed conduction in the bypass tract, thereby preventing subsequent A_3 conduction in the same conduction pathway. Figure 3 demonstrates the inner limit of the zone of concealed bypass tract conduction in the anterograde direction in the same patient. In Figure 3A, the A_2A_3 interval has been reduced to 180 ms (corresponding S_2S_3 interval of 160 ms) and both A_2 and A_3 fail to conduct in the bypass tract. In Figure 3B, A_2 is removed and conduction of A_3 is restored in the bypass tract. These findings again suggest that A_2 has concealed conduction in the bypass tract and, thus, influences subsequent A_3 conduction in the same conduction pathway.

Table 2. Electrophysiologic Data in 11 Patients

		Anterograde			Retrograde		
Case	CL (ms)	ERP_{AP} (ms)	ERP_{AT} (ms)	CC Zone* (ms)	ERP_{AP} (ms)	ERP_{RV} (ms)	CC Zone* (ms)
1	500	290	220	170 to 200/250	230	210	—
2	600	310	240	180 to 220/270	280	220	—
3	700	700†	230	—	360	280	250 to 280/310
4	600	280	220	180 to 230/250	230	210	—
5	600	320	210	200 to 240/240	290	230	—
6	600	600†	240	—	320	230	200 to 240/260
7	500	280	220	190 to 220/250	220	200	—
8	500	290	230	220 to 240/260	280	210	—
9	600	300	210	190 to 240/240	240	220	—
10	700	280	240	—	520	230	270 to 310/260
11	600	330	230	200 to 260/240	200	220	—

*Concealed conduction (CC) zone is expressed as A_2A_3/A_1A_2 interval in the anterograde direction and V_2V_3/V_1V_2 interval in the retrograde direction (see Methods section in text). †Capable only of retrograde conduction. CL = cycle length; ERP_{AP}, ERP_{AT} and ERP_{RV} = effective refractory period of anomalous pathway, atrium and right ventricle, respectively.

Retrograde concealed conduction of the anomalous AV bypass tract (Table 2). Retrograde concealed conduction was demonstrated in three patients (Cases 3, 6 and 10). The difference between the effective refractory period of the right ventricle and the retrograde effective refractory period of the bypass tract was greater than 80 ms in each of these patients. The width of the zones of concealed bypass tract conduction (between outer and inner limits of V_2V_3 intervals) ranged from 30 to 40 ms.

One example (Case 3) is illustrated in Figures 4 and 5. Figure 4 demonstrates the outer limit of the zone of concealed bypass tract conduction in the retrograde direction. In Figure 4A, right ventricular pacing at a cycle length (V_1V_1) of 700 ms results in lateral right atrial pre-excitation

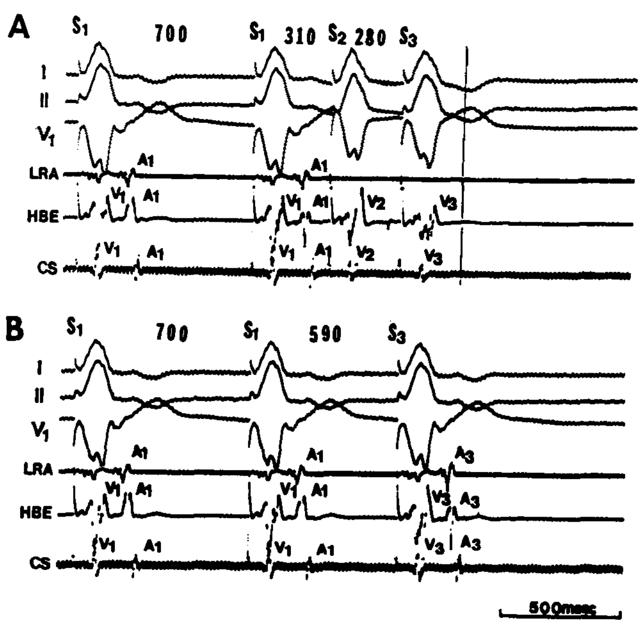


Figure 4. Case 3. Retrograde bypass tract concealed conduction (outer limit of the zone). **A**, V_2 and V_3 are blocked in a right-sided anomalous atrioventricular (AV) bypass tract during right ventricular (RV) pacing at a basic cycle length (V_1V_1) of 700 ms. The V_1V_2 and V_2V_3 intervals are 310 and 280 ms, respectively. **B**, Conduction of V_3 is restored in the anomalous AV bypass tract with removal of V_2. Electrocardiographic leads I, II and V_1, lateral right atrial electrogram (LRA), His bundle electrogram (HBE) and coronary sinus electrogram (CS) are shown. Atrial pre-excitation is seen in which lateral right atrial activation precedes low septal right atrial and left atrial (CS) activation during the basic drive.

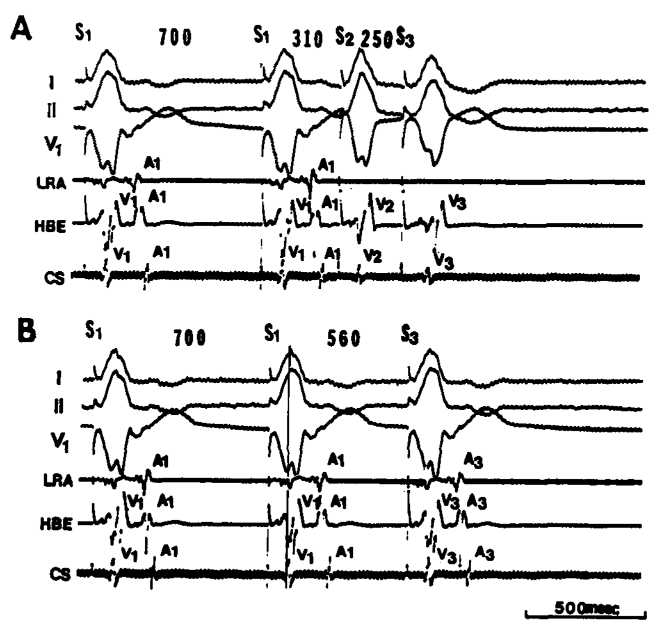


Figure 5. Case 3. Retrograde bypass tract concealed conduction (inner limit of the zone in the same patient as in Fig. 4). **A**, Compared with Figure 4 only the V_2V_3 interval has been reduced to 250 ms. V_2 and V_3 are also both blocked in the anomalous AV bypass tract. **B**, When V_2 is removed, conduction of V_3 is restored in the anomalous AV bypass tract.

with 1:1 ventriculoatrial conduction. The effective refractory period of the right ventricle and the retrograde effective refractory period of the bypass tract were, respectively, 280 and 360 ms. The V_1V_2 interval is fixed at 310 ms and the V_2V_3 interval is 280 ms. Both V_2 and V_3 are blocked in the bypass tract and the AV node. In Figure 4B, V_2 is removed and conduction of V_3 in the bypass tract is restored. The return of V_3 retrograde bypass tract conduction implies that V_2, which is blocked in the bypass tract, has concealed conduction in the bypass tract thereby preventing subsequent V_3 conduction in the same conduction pathway. Figure 5 demonstrates the inner limit of the zone of concealed bypass tract conduction in the retrograde direction in the same patient. In Figure 5A, the V_2V_3 interval has been shortened to 250 ms, and both V_2 and V_3 are also blocked in the bypass tract and the AV node. In Figure 5B, V_2 is removed and conduction of V_3 is restored in the bypass tract. These findings again suggest that V_2 has concealed conduction in the bypass tract and, thus, influences subsequent V_3 conduction in the same conduction pathway.

Discussion

In the human heart, concealed conduction has been frequently observed in the AV node and His-Purkinje system (5–8). It has also recently been shown to occur in the atrium (9). This study is an extension of our previous work (17) which is the first in which concealed conduction in anomalous AV bypass tracts has ever been systematically assessed. Using a similar study method, other investigators (18) have subsequently confirmed our observations.

The $S_1S_2S_3$ method. With the $S_1S_2S_3$ method of programmed electrical stimulation (Fig. 1), the presence of A_2 or V_2, which was blocked in the bypass tract, prevented subsequent A_3 or V_3 conduction in the same conduction pathway despite the A_1A_3 or V_1V_3 interval being longer than the anterograde or retrograde effective refractory period of the bypass tract. Removal of A_2 or V_2 invariably resulted in the resumption of A_3 or V_3 conduction in the bypass tract (Fig. 2 to 5). These findings meet the definition of concealed conduction (1). The possibility that A_2 and A_3 during atrial pacing were actually blocked in the ventricle was deemed unlikely as the effective refractory period of the ventricle was shorter than the A_1A_2 and A_1A_3 intervals in each case. Conversely, the V_1V_2 and V_1V_3 intervals during ventricular pacing were always longer than the effective refractory period of the atrium in each case, ruling out block of V_2 and V_3 in the atrium.

Factors influencing demonstration of concealed bypass tract conduction. Using the $S_1S_2S_3$ method, the demonstration of concealed bypass tract conduction depends on the effective refractory periods of the atrium, ventricle and the anomalous AV bypass tract, and probably also on the location of the pacing site relative to that of the anomalous AV bypass tract. Anterograde concealed bypass tract conduction is better demonstrated when the anterograde effective refractory period of the bypass tract is greater than that of the atrium. Likewise, retrograde concealed bypass tract conduction is better demonstrated when the retrograde effective refractory period of the bypass tract is longer than that of the ventricle. An anomalous AV bypass tract with a short anterograde or retrograde effective refractory period ($\leq$ that of the atrium or $\leq$ that of the ventricle, respectively) often precludes demonstration of concealed bypass tract conduction, respectively, in the anterograde or retrograde direction using this method. However, if an anomalous AV bypass tract has an effective refractory period greater than that of the basic driving cycle length, the $S_1S_2S_3$ method cannot be applied to demonstrate concealed bypass tract conduction in the corresponding anterograde or retrograde direction because of constant block in the anomalous AV bypass tract.

Clinical and electrophysiologic implications. The occurrence of concealed bypass tract conduction in both anterograde and retrograde directions is one of the factors regulating the rate of ventricular response during atrial flutter-fibrillation in the Wolff-Parkinson-White syndrome (14,15). Although our study has demonstrated that concealed conduction does occur in the anomalous AV bypass tract, the exact site at which it occurs remains to be determined. Further studies should be aimed at direct recording of bypass tract depolarization (19,20).

There are several means by which concealed bypass tract conduction can be demonstrated. Quantification of concealed conduction remains difficult. The clinical significance of the zone of concealed bypass tract conduction (A_2A_3 and V_2V_3 intervals) so measured can only be speculative. The inner limit of the zone of concealed bypass tract conduction is limited by the refractoriness of the atrium or ventricle to S_3 (A_3 or V_3). The outer limit of the zone is a reflection of a "new" effective refractory period of the anomalous AV bypass tract resulting from concealed conduction of A_2 or V_2 in the bypass tract and the sudden change of the pacing cycle length from A_1A_1 or V_1V_1 to A_1A_2 or V_1V_2. It is tempting to suggest that the effects of pharmacologic interventions on the zone of concealed conduction may be as important as other factors influencing the ventricular rate during atrial flutter-fibrillation in the Wolff-Parkinson-White syndrome.

We gratefully acknowledge Jan Perini and Steven Burns for their excellent assistance in the preparation of this manuscript.

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