A fourth criterion for transient entrainment: the electrogram equivalent of progressive fusion

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ABSTRACT Prior data pertaining to transient entrainment and associated phenomena have been best explained by pacing capture of a reentrant circuit. On this basis, we hypothesized that rapid pacing from a single site at two different constant pacing rates could constantly capture an appropriately selected bipolar electrogram recording site from one direction with a constant stimulus-to-electrogram interval during pacing at one rate, yet be constantly captured from another direction with a different constant stimulus-to-electrogram interval when pacing at a different constant pacing rate. To test this hypothesis, we studied a group of patients, each with a representative tachycardia (ventricular tachycardia, circus-movement tachycardia involving an atrioventricular bypass pathway, atrial tachycardia, and atrial flutter). For each tachycardia, pacing was performed from a single site for at least two different constant rates faster than the spontaneous rate of the tachycardia. We observed in these patients that a local bipolar recording site was constantly captured from different directions at two different pacing rates without interrupting the tachycardia at pacing termination. The evidence that the same site was captured from a different direction at two different pacing rates was supported by demonstrating a change in conduction time to that site associated with a change in the bipolar electrogram morphology at that site when comparing pacing at each rate. The mean conduction time (stimulus-to-recording site electrogram interval) was 319 ± 69 msec while pacing at a mean cycle length of 265 ± 50 msec, yet only 81 ± 38 msec while pacing at a second mean cycle length of 233 ± 51 msec, a mean change in conduction time of 238 ± 56 msec. Remarkably, the faster pacing rate resulted in a shorter conduction time. The fact that the same electrode recording site was activated from different directions without interruption of the spontaneous tachycardia at pacing termination is difficult to explain on any mechanistic basis other than reentry. Also, these changes in conduction time and electrogram morphology occurred in parallel with the demonstration of progressive fusion beats on the electrocardiogram, the latter being an established criterion for transient entrainment. Based on these data, we propose that a change in conduction time to a recording site associated with a change in the bipolar electrogram morphology at that site when pacing during a tachycardia from a single pacing site at two different constant rates is an independent criterion for establishing the presence of transient entrainment, and further supports the notion that the demonstration of transient entrainment indicates an underlying reentry mechanism.

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We first recognized the phenomenon of transient entrainment in 1977 while studying atrial flutter by rapid atrial pacing techniques.1 Subsequent studies during circus-movement tachycardia involving an atrioventricular bypass pathway,2,3 ventricular tachycardia4-10 atrial flutter,11,12 atrial tachycardia,13 and atrioventricular nodal reentrant tachycardia14,15 have demonstrated that transient entrainment indicates pacing capture of a putative reentry circuit and thus is a marker for reentrant tachyarrhythmias. We have previously proposed three criteria for identification of transient entrainment (criteria 1 to 3, table 1), any one of which, if fulfilled, confirms the presence of transient entrainment, and thereby presumably reentry.

Previous data have indicated that the phenomenon of transient entrainment is best explained by pacing capture of a reentry circuit from two directions. The phenomenon of progressive fusion (criterion 2, table 1), which indicates a change in activation during capture

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of a reentry circuit when comparing pacing from the same site at two different rates during a tachycardia, strongly supports such an explanation. Thus, it is logical that a local electrogram could demonstrate capture from two directions at two different rates, i.e., the electrogram equivalent of progressive fusion, when comparing pacing from the same site at two different rates during a tachycardia. We therefore hypothesized that during rapid pacing from a single site at two different constant pacing rates, an appropriately selected bipolar electrogram recording site could be constantly captured from one direction with a constant stimulus-to-electrogram interval during pacing at one rate, yet be constantly captured from another direction with a different constant stimulus-to-electrogram interval when pacing at a different constant pacing rate. These phenomena should be identifiable when pacing from a single site during a tachycardia if both a change in conduction time to and bipolar electrogram morphology at a recording site occur when pacing at two different constant rates that do not interrupt the tachycardia.

In this study, we demonstrate that the above-described phenomena do occur. Furthermore, we propose that they are an independent criterion for the demonstration of transient entrainment and permit the demonstration of transient entrainment when fusion beats on the electrocardiogram (ECG) (required for criteria 1 and 2, table 1), particularly atrial fusion beats, are difficult to recognize.

Methods
A group of four patients with four representative arrhythmias were studied: one with ventricular tachycardia, one with circus-movement tachycardia with a left-sided atrioventricular bypass pathway, one with atrial tachycardia, and one with classical (type I) atrial flutter. All patients underwent electrophysiologic study during cardiac catheterization while in the postabsorptive state with the use of standard cardiac electrophysiologic and rapid pacing techniques, as previously described.2 No patients were receiving antiarrhythmic therapy at the time of study.

After informed consent was obtained, during sustained tachycardia each patient underwent rapid pacing from selected sites at selected constant rates that were faster than the spontaneous tachycardia rate but which failed to interrupt the tachycardia. Pacing at each rate was performed for 15 to 30 sec, during which time there was clear demonstration of constant capture and stability of local conduction times. Simultaneous ECGs and electrograms were used to confirm capture of all cardiac tissue involved in the respective arrhythmia: during pacing of ventricular tachycardia, all recorded ventricular electrograms and electrocardiographic QRS complexes were captured at the pacing rate; during pacing of atrial flutter and atrial tachycardia, all recorded atrial electrograms and electrocardiographic atrial complexes were captured at the pacing rate; during pacing of circus-movement tachycardia, all recorded electrograms (atrial, His, ventricular) and all electrocardiographic complexes (P waves and QRS complexes) were captured at the pacing rate.

Table 1
Criteria for the demonstration of transient entrainment of a tachycardia

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Description</th>
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<tbody>
<tr>
<td>(1)</td>
<td>During tachycardia, while pacing at a constant rate that is faster than the rate of the spontaneous tachycardia and that fails to interrupt it, the demonstration of constant fusion beats in the electrocardiogram, except for the last captured beat, which is not fused.</td>
</tr>
<tr>
<td>(2)</td>
<td>During tachycardia, while pacing at two or more constant rates that are faster than the rate of the spontaneous tachycardia but that fail to interrupt the tachycardia, the demonstration of constant fusion beats on the ECG at each rate, but different degrees of constant fusion at each rate (progressive fusion).</td>
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<tr>
<td>(3)</td>
<td>During tachycardia, while pacing at a constant rate faster than the rate of the spontaneous tachycardia that interrupts the tachycardia, the demonstration of localized conduction block to a site(s) for 1 beat followed by activation of that site(s) by the next paced beat from a different direction and with a shorter conduction time.</td>
</tr>
<tr>
<td>(4)</td>
<td>During tachycardia, when pacing at two constant rates that are faster than the rate of the spontaneous tachycardia but that fail to interrupt the tachycardia, the demonstration of a change in conduction time to and electrogram morphology at an electrogram recording site.</td>
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Pacing was performed at twice diastolic threshold with a Medtronic 1349A programmable pacemaker. All data were recorded with an Electronics-for-Medicine DR12 or VR16 oscilloscopic recorder. All data were also simultaneously recorded on a Honeywell 5600C FM tape recorder for subsequent playback and analysis. All measurements were made from data recorded at a speed of 100 mm/sec.

Critical to the study were the observations made at a single electrode recording site while pacing during the respective tachycardia at two constant but different rates. If a difference in conduction time to and bipolar electrogram morphology at a recording site was documented when comparing pacing at the two rates, the recording site was considered to be captured from two different directions. Therefore, while pacing at each constant rate (at least two rates, each greater than the tachycardia rate), particular attention was devoted to the measurement and the analysis of the conduction time (interval from the stimulus artifact to the electrogram recorded at each site) and to the morphology of the bipolar electrograms recorded at each electrogram recording site. The tachycardias were all subsequently interrupted by rapid pacing.

Results
Table 2 summarizes the salient information from the study patients. There was an average arrhythmia cycle length of 301 ± 60 msec for the study group. While pacing during the tachycardia at the slower of two rates faster than the tachycardia (average pacing cycle length of 265 ± 50 msec), the mean stimulus-to-electrogram interval (conduction time) was 319 ± 69 msec, yet there was no interruption of any arrhythmia on pacing termination. While pacing at the second rate faster than the tachycardia (an average cycle length of 233 ± 51 msec), which did not interrupt the tachycardia, the mean conduction time was only 81 ± 38 msec. This was a marked change of 238 ± 56 msec in the mean conduction time between the two rates.
Thus, remarkably, the mean conduction time to the recording site(s) markedly decreased in response to a faster pacing rate as each patient demonstrated a decrease in conduction time (table 2). Furthermore, for each tachycardia, the bipolar electrogram at the electrode recording site was constantly captured at each pacing rate, yet the electrogram morphology was different at each rate. As the illustrations below will highlight, these substantial changes in conduction time and electrogram morphology while pacing at two different rates are best explained by capture of the recording site from two different directions in or around a reentrant circuit. These phenomena are the fourth criterion for transient entrainment (table 1).

**Ventricular tachycardia**

Demonstration of entrainment criteria No. 1 and 2. Figure 1 illustrates electrocardiographic leads I and V1 recorded simultaneously with bipolar electrograms from the high right atrium, the proximal and distal electrode pairs of a quadripolar electrode catheter placed at the right ventricular apex, and the proximal and distal electrode pairs of a quadripolar electrode catheter placed in the left ventricle in a patient with a monomorphic, right bundle branch block morphology ventricular tachycardia at a cycle length of 360 msec (patient 1, table 2). Pacing was performed during the ventricular tachycardia from the distal electrode pair of the electrode catheter placed at the right ventricular apex at selected cycle lengths that included 300 and 250 msec for at least 15 sec, with resumption of the tachycardia at pacing termination (figure 2). Pacing at 300 msec (figure 2, A) demonstrated constant fusion beats on the ECG except for the last beat captured at the pacing cycle length, as identified by the left ventricular electrogram, which was not fused. In addition, constant pacing at cycle lengths of 300 msec (panel A) and 250 msec (panel B) demonstrated different degrees of constant fusion at each rate, i.e., progressive fusion was identified on the ECG. Thus, rapid pacing during this ventricular tachycardia illustrated criterion 1 and

![Figure 1](http://example.com/figure1.png)

**FIGURE 1.** Electrocardiographic leads I and V1 recorded simultaneously with bipolar electrograms from the high right atrium (HRA), proximal (RVp) and distal (RVd, attenuated for pacing) right ventricular apex, and proximal (LVp) and distal (LVd) left ventricle during right bundle branch block morphology ventricular tachycardia (cycle length of 360 msec) with atrioventricular dissociation. See text for discussion.

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**TABLE 2**

Summary of patient data

<table>
<thead>
<tr>
<th>Patient No.</th>
<th>A</th>
<th>CL</th>
<th>PS</th>
<th>RS</th>
<th>PCL₁</th>
<th>CT₁</th>
<th>PCL₂</th>
<th>CT₂</th>
<th>CT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>VT</td>
<td>360</td>
<td>RVA</td>
<td>LVp</td>
<td>300</td>
<td>365</td>
<td>250</td>
<td>120</td>
<td>245</td>
</tr>
<tr>
<td>2</td>
<td>CMT</td>
<td>340</td>
<td>HRA</td>
<td>CS</td>
<td>308</td>
<td>390</td>
<td>292</td>
<td>90</td>
<td>300</td>
</tr>
<tr>
<td>3</td>
<td>AT</td>
<td>275</td>
<td>HRA</td>
<td>RAM</td>
<td>250</td>
<td>270</td>
<td>220</td>
<td>30</td>
<td>240</td>
</tr>
<tr>
<td>4</td>
<td>AFL</td>
<td>230</td>
<td>HRA</td>
<td>CS</td>
<td>200</td>
<td>250</td>
<td>170</td>
<td>85</td>
<td>165</td>
</tr>
</tbody>
</table>

Mean ± SD 301 ± 60 265 ± 50 319 ± 69 233 ± 51 81 ± 38 238 ± 56

**Time intervals are in msec.**

A = arrhythmia (VT = ventricular tachycardia; CMT = circus-movement tachycardia using left-sided bypass tract; AT = atrial tachycardia; AFL = atrial flutter); CL = cycle length; PS = pacing site (RVA = right ventricular apex; HRA = high right atrium); RS = recording site (LVp = left ventricular, proximal; CS = coronary sinus; RAM = mid right atrium); PCL₁ = pacing cycle length 1; CT₁ = conduction time at PCL₁ (stimulus to RS electrogram time); PCL₂ = pacing cycle length 2; CT₂ = conduction time at PCL₂; CT = difference in conduction times from pacing at PCL₁ and PCL₂ (CT₁ minus CT₂).
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FIGURE 2. Electrocardiographic leads I and V1 and electrograms recorded from the same patient as in figure 1 at the termination of rapid ventricular pacing from the right ventricular apex at a cycle length of 300 msec (A) and 250 msec (B). During the period of pacing at each cycle length, constant ventricular capture was obtained, and there were constant fusion beats on the ECG, except during pacing at a cycle length of 300 msec when the last beat was captured at the pacing cycle length, but was not fused (first criterion for transient entrainment). This is evident because the last captured left ventricular proximal (LVp) and distal (LVd) electrograms at the 300 msec rate are associated with the electrocardiographic QRS complex morphology of spontaneous tachycardia. When comparing the morphology of the QRS complexes during pacing at each cycle length, note that the morphology during pacing at a cycle length of 300 msec is intermediate between that produced by the ventricular tachycardia and that expected from pacing from the right ventricular apex, whereas during pacing at a cycle length of 250 msec, it is more like that expected during overdrive pacing of sinus rhythm from the right ventricular apex. Thus, together, A and B demonstrate progressive fusion on the ECG (second criterion for transient entrainment). Of note, there are two other important comparative observations during transient entrainment at each cycle length. During pacing at a cycle length of 300 msec, the electrograms recorded from the LVp and LVd sites have similar, if not identical, morphologies during pacing and during the spontaneous rhythm, and conduction time (curved arrow) from the stimulus to the LVp site is long at 365 msec (encircled). The conduction time to the LVd site of 360 msec is not indicated on the illustration. However, during pacing at a cycle length of 250 msec, electrogram morphologies at the LVp and LVd sites are clearly different than during the spontaneous tachycardia and during pacing capture in A. Also, the conduction time from the stimulus to the LVp site is much shorter at 120 msec (encircled). The conduction time to the LVd site of 125 msec is not indicated on the figure. Thus, there is a change in conduction time to and bipolar electrogram morphology at the LVp recording site (and LVd recording site) when comparing constant ventricular pacing at two different cycle lengths. Because the last clearly captured beat at the pacing cycle length of 250 msec (B) is associated with a fusion complex, the first criterion for transient entrainment is not fulfilled. S = stimulus artifact. All values are in msec. See text for discussion.

criterion 2 for the demonstration of transient entrainment (table 1).

Demonstration of the fourth criterion for ventricular tachycardia. As shown in figure 2, A, while pacing from the right ventricular apex at a cycle length of 300 msec, the electrograms recorded from the quadripolar catheter placed in the left ventricle demonstrated a morphology similar to that during the spontaneous tachycardia. Furthermore, the conduction time from the pacing stimulus to the proximal left ventricular recording site was 365 msec (and that to the distal left ventricular site was 360 msec). On the other hand, while pacing at a cycle length of 250 msec from the same site (figure 2, B), the electrograms from the same proximal left ventricular and distal left ventricular sites each had a different morphology and were captured with shorter conduction times of 120 and 125 msec, respectively.

Figure 3 shows a diagrammatic representation of spontaneous ventricular tachycardia based on the model of Wit et al.16 and El-Sherif et al.17 (panel A), transient entrainment of the ventricular tachycardia at a pacing cycle length of 300 msec (panel B), and then subsequent transient entrainment at a pacing cycle length of 250 msec (panel C). With pacing at a constant rate somewhat faster than that of the spontaneous reentrant arrhythmia (panel B), the wavefront from the pacing impulse entered the excitable gap of the reentry circuit with resultant constant capture, both in the same direction as the circulating wavefront of the spontaneous tachycardia (i.e., orthodromically) and in the opposite direction (i.e., antidromically). Each antidromic wavefront (x + 1) collided with the preceding orthodromic wavefront (x), producing a fusion QRS complex morphology on the ECG. During transient entrainment at a constant pacing rate, the site of collision of each antidromic wavefront with the preceding orthodromic wavefront occurred at a constant location, explaining the presence of constant fusion beats (QRS complexes) on the ECG during transient entrainment. By examining activation at the electrogram recording
sites, particularly site EG2, it can be appreciated that when the excitation wavefront during rapid pacing reached an electrogram recording site from the same direction as during the spontaneous tachycardia, i.e., orthodromically, the electrogram morphology at that recording site was similar, if not identical, to that during the spontaneous tachycardia (panel B). In addition, during constant capture at a constant pacing rate, conduction time to that site (represented by the interval from the stimulus artifact to the electrogram recorded at that site) remained constant. On the other hand, as noted in panel C, when the constant pacing rate was changed, in this example increased, there was further antidromic penetration of the wavefront from each stimulus such that a recording site (EC2) previously activated from the orthodromic direction was constantly activated from the antidromic direction. When this occurred, it was associated with a change in both the conduction time to and electrogram morphology at the EG2 recording site when comparing the two constant but different rates. This change was associated with a different degree of constant fusion of the QRS complex on the surface ECG (figure 2).

In summary, figure 3 diagrammatically illustrates localized events during progressive fusion on the ECG. At a specific recording site, there was a change in conduction time and bipolar electrogram morphology while pacing a ventricular tachycardia at two different constant rates. This is explained by activation (capture) of the specific recording site from a different direction at each of the two rapid pacing rates. As the following examples will show, the phenomenon of a change in conduction time to a specific electrogram recording site associated with a change in the bipolar electrogram...
morphology recorded at that site can be observed in other reentrant arrhythmias as well.

Circus-movement tachycardia with an atrioventricular bypass pathway. In a second representative example (patient 2, table 2), we observed constant capture during two constant pacing rates of an orthodromic circus-movement tachycardia that used a left lateral atrioventricular bypass pathway for retrograde conduction from the ventricles to the atria (figure 4). This example was taken from one of our previous publications because it so well illustrates the entire thrust of this presentation.

Figure 4 shows termination of atrial pacing from a high right atrial site after constant pacing at a cycle length of 308 msec (panel A) and 292 msec (B) during a circus-movement tachycardia whose spontaneous cycle length was 340 msec. In each example, during the period of constant rate pacing, all recording sites were activated at the pacing rate. Focusing on atrial events at the coronary sinus recording site during and after termination of pacing, note in panel A that the spontaneous arrhythmia resumes after termination of pacing and that the morphology of the coronary sinus electrogram is the same during pacing and during the spontaneous tachyarrhythmia. Thus, the coronary sinus site is activated from the same direction (i.e., orthodromically) during pacing as during the spontaneous tachyarrhythmia. Also note the very long conduction time of 390 msec from the stimulus to the atrial potential of the coronary sinus electrogram.

As shown in figure 4, B, while pacing at a cycle length of 292 msec from the same high right atrial site, the coronary sinus recording site was again activated at the pacing rate. However, note that the morphology of the coronary sinus electrogram was different than during pacing at a cycle length of 308 msec (panel A) and than during the spontaneous tachycardia (panels A and B after pacing termination), indicating that this atrial site was being activated from a different direction. Note also in panel B that activation at this site was associated with a shorter conduction time from the stimulus site of only 90 msec. Furthermore, despite the electrogram changes, constant atrial fusion beats were difficult to discern on the ECG. Thus, the observation of a change in conduction time to an atrial recording site associated with a change in electrogram morphology recorded at that site was a particularly useful criterion in establishing transient entrainment of this reentrant supraventricular tachycardia. In fact, in this example, the change in conduction time to the coronary sinus recording site and the change in atrial electrogram morphology at that recording site was the only way one could extrapolate that there must have been progressive fusion when comparing pacing at the two different rates. It was this very argument that was used in the initial presentation of the data from this figure (comparing panels A and B) to establish that atrial fusion beats were present in panel A and that progressive fusion must have taken place.

Atrial tachycardia. The phenomena of a change in...
FIGURE 5. A, ECG lead II recorded simultaneously with electrograms from the distal (HRAd), mid (HRAm), and proximal (HRAp) electrodes of a hexapolar electrode catheter placed in the high right atrium, and from the coronary sinus (CS) during termination of constant rapid atrial pacing at a cycle length of 250 msec in a patient during an atrial tachycardia with a cycle length of 275 msec. The conduction time (curved arrow) from the pacing site to the HRAm recording site is 270 msec (encircled number). Also, note that during rapid pacing, the electrogram morphology recorded from the HRAm site is similar, if not identical, to the electrogram morphology during the spontaneous arrhythmia. The HRAp and CS electrograms are activated with very long conduction times of 250 and 190 msec, respectively (not indicated on the figure). S = stimulus artifact. All values are in msec. See text for discussion. B, The same tracings recorded during atrial tachycardia from the same patient as in A at the termination of rapid atrial pacing at a cycle length of 220 msec. In contradistinction to pacing at a cycle length of 250 msec, conduction time (arrow) from the pacing site to the HRAm recording site is only 30 msec (encircled number). Also, in contradistinction to that with constant pacing at a cycle length of 250 msec, the morphology of the HRAm electrogram is quite different than that during the spontaneous atrial tachycardia. Thus, there was a change in conduction time to and bipolar electrogram morphology at the HRAm recording site during rapid atrial pacing at two different constant pacing cycle lengths. Interestingly, the HRAp and CS recording sites were still captured with long conduction times of 250 msec and 190 msec, respectively (not indicated on the figure). Note that progressive atrial fusion beats cannot be discerned on the ECG despite changes in the electrogram recordings. S = stimulus artifact. All values are in msec. See text for discussion.

Conduction time to a local recording site associated with a change in electrogram morphology at that site when comparing pacing at two different constant pacing rates has also been identified in atrial tachycardia, as shown below. Figure 5 illustrates the termination of rapid atrial pacing at two different constant rates during an atrial tachycardia with a spontaneous cycle length that varied between 275 and 280 msec. During spontaneous atrial tachycardia, there was variable atrioventricular conduction block (generally 2:1) to the ventricles, thus excluding the atrioventricular node and the ventricles as necessary parts of the arrhythmia. Furthermore, criterion 3 (table 1) was demonstrated at arrhythmia interruption, indicating that the atria (no illustration), but not the atrioventricular node or ventricle, were essential for sustenance of the arrhythmia. Note that during atrial pacing at each constant cycle length (250 msec in figure 5, A, and 220 msec in figure 5, B), the morphology of the atrial complex in electrocardiographic lead II was not that expected with high right atrial pacing. This indicated the likely presence of constant fusion beats, except for the last beat, which was captured at the pacing cycle length, but was not fused (criterion 1, table 1). However, the clear identification of progressive fusion of the atrial complexes on the ECG (criterion 2) is actually quite difficult, since atrial complexes on the ECG during atrial pacing and during the spontaneous arrhythmia are very similar. There may be some flattening of the morphology of the atrial complex during pacing at a cycle length of 250 msec when compared with that during spontaneous tachyarrhythmia, but this is not certain.

However, when examining the atrial electrograms recorded from the high right atrium during pacing at each rate, it is clear that there were changes in conduction time and bipolar electrogram morphology in the recordings from the mid high right atrial site. The bipolar atrial recordings were obtained with a hexapolar catheter in which the electrodes of a recording pair were separated by 2 mm and each adjacent recording pair was separated by 1 cm. Pacing from the distal electrode pair at a cycle length of 250 msec (figure 5, A) resulted in the capture of the mid right atrial recording site with a long conduction time (stimulus-to-electrogram interval) of 270 msec. Also, note that the morphology of the mid right atrial electrogram was identical during rapid pacing and spontaneous tachycardia.

On the other hand, as shown in figure 5, B, during pacing of the atrial tachycardia at a cycle length of 220 msec, it was obvious at the mid right atrial recording site that there had been a change in the atrial electrogram morphology associated with a much shorter conduction time (stimulus-to-electrogram interval) of 30 msec. Therefore, figure 5 panels A and B reveal a change in conduction time and bipolar electrogram morphology at the mid right atrial recording site, indicating activation of this recording site from a different direction at each constant pacing rate.

Atrial flutter. Figure 6, A, shows the termination of rapid atrial pacing at a cycle length of 200 msec after capture of the atria in a patient with atrial flutter (spontaneous cycle length of 230 msec). It is clear that the atrial potentials recorded from the high right atrium and
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FIGURE 6. A, Electrocardiographic lead II recorded simultaneously with the electrograms from the high right atrium (HRA) and coronary sinus (CS) during pacing from the high right atrium at a cycle length of 200 msec during atrial flutter with a spontaneous cycle length of 230 msec. During the period of constant pacing, conduction time (curved arrow) from the pacing site to the atrial electrogram of the CS recording site is 250 msec (encircled number), and the atrial electrogram recorded at the CS site is similar, if not identical, in morphology during the period of rapid atrial pacing and the spontaneous atrial flutter. All values are in msec. S = stimulus artifact. See text for discussion. B, Same tracings recorded from the same patient as in A at the termination of rapid atrial pacing at a cycle length of 170 msec during the same atrial flutter. In contradistinction to that with pacing at a cycle length of 200 msec, conduction time (arrow) from the pacing site to the CS recording site is only 85 msec (encircled number). Also, in contradistinction to that with pacing at a cycle length of 200 msec, the morphology of the atrial electrogram recorded at the CS site is quite dissimilar to that during spontaneous atrial flutter. The atrial complex on the ECG during pacing is upright, distinctly different from A. Most importantly, there is a change in conduction time to and bipolar electrogram morphology at the CS recording site when comparing constant pacing of atrial flutter at two different but constant pacing cycle lengths. All values are in msec. S = stimulus artifact. See text for discussion.

the coronary sinus sites are constantly captured at the 200 msec pacing cycle length until pacing is terminated. The stimulus-to-atrial electrogram interval at the coronary sinus site was 250 msec and the morphology of the bipolar atrial electrogram recorded from the coronary sinus site was similar, if not identical, to that during the spontaneous arrhythmia.

As shown in figure 6, B, atrial pacing at a cycle length of 170 msec again resulted in constant capture of the high right atrium and coronary sinus sites at the pacing cycle length until pacing was terminated. The atrial complex in electrocardiographic lead II became upright, as one might anticipate when pacing from high in the right atrium. In addition, the morphology of the atrial electrogram at the coronary sinus site during pacing at this cycle length changed, and conduction time to this site was 85 msec compared with 250 msec at the previous pacing rate (figure 6, A). However, when pacing was terminated, the tachycardia was not interrupted, but continued at the original atrial flutter cycle length with the same atrial electrogram morphology as recorded at the coronary sinus site before. Thus, rapid atrial pacing at two different constant cycle lengths demonstrated that a local recording site (the coronary sinus site, in this case) was activated in the same direction as during the spontaneous atrial flutter, with the morphology of the atrial electrogram similar to that during the spontaneous atrial flutter with a long stimulus-to-electrogram interval at one constant pacing rate (cycle length 200 msec). However, at a faster constant pacing rate (cycle length 170 msec), atrial activation at that same site occurred with a different atrial electrogram morphology associated with a shorter conduction time than during the previous pacing rate. Thus, in this representative example of rapid atrial pacing during atrial flutter, a change in bipolar electrogram morphology and conduction time during rapid pacing at two different constant rates was clearly evident.

Discussion

This study focuses on the local bipolar electrograms recorded from selected sites during rapid pacing in a group of patients with four different reentrant arrhythmias. Most important during this study was the demonstration that during pacing from a single site during an arrhythmia, a local bipolar recording site was activated from one direction when pacing at one constant rate, but from another direction when pacing at a different constant rate, in each instance without interrupting the arrhythmia. This observation, as noted in all our patients (table 2 and figures 2, 4, 5, and 6), is what one would anticipate if a specific recording site in or near a reentrant circuit was activated from the same direction as during the spontaneous arrhythmia (orthodromically) at one constant pacing rate, but from another direction relative to the reentrant circuit (antidromically) during another constant, but different, pacing rate. In fact, we submit that these observations are an independent criterion for the demonstration of transient entrainment, and also that changes in conduction time and bipolar electrogram morphology that occur during constant pacing of an arrhythmia at two different constant rates are best explained by the presence of an underlying reentrant rhythm.

Relationship of the fourth criterion to previous criteria.
The elucidation of the fourth criterion for transient
entainment is a natural evolution from the concepts, both implicit and explicit, that are central to the first three criteria. As particularly well documented by the example of the transient entainment of ventricular tachycardia (figure 2), the fourth criterion occurs in parallel with the electrocardiographic events associated with criteria 1 and 2 (table 1). Thus, as illustrated (figure 2, A), during pacing at one rate, the last captured electrogram at the proximal left ventricular site is associated with a QRS complex on the ECG that is captured, but not fused (criterion 1). Then, as illustrated (figure 2, B), there is the demonstration of the local activation changes of the fourth criterion (a change in conduction time to and bipolar electrogram morphology at an electrogram recording site) associated with progressive fusion on the ECG. The third criterion (table 1), not illustrated herein, also rests on a change in conduction time to and morphology recorded at one electrogram recording site. The third criterion is demonstrated when an electrogram recording site shows localized conduction block for 1 beat, associated with interruption of the tachycardia while pacing at a constant rate (table 1). In summary, while each criterion is independently sufficient to demonstrate transient entainment, all the criteria are related, because they rest on the same concepts and support the notion of pacing capture of a reentrant circuit. However, the fourth criterion, while predictable from what we know about the events associated with the first three criteria, has its unique aspects and can be observed when the other criteria are not (e.g., figure 4).

Relationship of fourth criterion to identifying the presence of reentry. We have previously suggested that data that led to the evolution of the first three criteria were best explained by reentry. Present understanding of the pacing response of rhythms due to automaticity is quite inconsistent with the phenomena of constant fusion beats on the ECG except for the last captured beat, progressive fusion on the ECG, and localized conduction block associated with interruption of the arrhythmia (table 2) previously described during transient entrainment and subsequent interruption of a tachycardia by rapid pacing. Conceptually, overdrive pacing of an automatic or triggered "focus" that generates a tachycardia should not result in constant fusion beats on the ECG, since the entire chamber(s) being paced is captured by the pacing stimulus, suppressing the expression of the "focus." If there is entrance block into an automatic focus, variable fusion as opposed to the constant fusion beats of transient entrainment should be observed.

Likewise, the observations associated with the fourth criterion are also difficult to explain except by reentry. The relevant observations are that during rapid pacing of a tachycardia from the same site at two different constant rates faster than the tachycardia rate (1) a single recording site is activated from two different directions during pacing at two different rates, and (2) conduction time from the stimulus site to the same recording site is shorter at the faster of the two rates. Constant capture of a particular recording site from two different directions during two different constant rates has not been appreciated with either overdrive suppression of an automatic focus or overdrive pacing of a triggered rhythm. Also, overdrive pacing of an automatic or triggered rhythm would result in capture of any adjacent recording site from the same direction despite the pacing rate, unlike that seen with the fourth criterion.

In addition, neither one of the fourth criterion observations alone could be explained simply by what we know about conduction and block. For example, if the direction of activation of a site changed because conduction block occurred while pacing, such that a wavefront from a pacing impulse had to travel around a site of block to capture a recording site, one would anticipate a longer conduction time at the faster rate, not a shorter conduction time as noted with the fourth criterion. To explain this observation, one would have to postulate that block were present during pacing at the slower rate and disappeared with pacing at the faster rate. Thus, we suggest that figure 3 in schematic form best explains the phenomenon we propose as the fourth criterion for transient entainment.

Limitations. Conceptually, one should be able to demonstrate the fourth criterion during most tachycardias due to macroreentry with an excitatory gap. However, in practice, this may not always be possible. For instance, in tachycardias due to reentry involving an anatomically small reentrant circuit, recording from an electrode site that could demonstrate this criterion may be technically difficult or impossible, e.g., as with atrioventricular nodal reentry. Even for a large reentrant circuit, extensive electrode catheter mapping may be required to find a suitable electrode recording site. Furthermore, the characteristics of the components of the reentry circuit, particularly the response of the putative area of slow conduction to pacing, will also affect the ability to demonstrate the fourth criterion. It is conceivable that with pacing at any rate faster than the tachycardia rate, conduction through the area of slow conduction may be so prolonged that antidromic activation of most, if not all, the reentry circuit would
occur. If that happens, it would be extremely difficult, if not impossible, to demonstrate the fourth criterion or other criteria. In addition, the site of pacing is important, since the presence of transient entrainment that cannot be demonstrated by criteria 1 to 3 during pacing from one site has been demonstrated when pacing from another site at similar rates.

All of the above makes it difficult to predict the frequency with which one would be able to demonstrate the fourth criterion. Certainly, the present study does not permit speculation on this aspect of transient entrainment. Nevertheless, the demonstration of the fourth criterion further supports the concept that transient entrainment represents the pacing capture of a reentry circuit.

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A fourth criterion for transient entrainment: the electrogram equivalent of progressive fusion.
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