Sequence of Retrograde Atrial Activation in Patients with Dual Atrioventricular Nodal Pathways

RUEY J. SUNG, M.D., HARVEY L. WAXMAN, M.D., SANJEEV SAKSENA, M.D., AND ZULFIKAR JUMA, M.D.

SUMMARY To characterize the sequence of retrograde atrial activation in the presence of dual atrioventricular (AV) nodal pathways, we analyzed electrophysiologic data from seven patients in whom discontinuous AV nodal and ventriculoatrial conduction curves could be induced with programmed electrical stimulation. In all patients, electrograms of the high right atrium (HRA), lateral right atrium (LRA), low septal right atrium (SRA) and proximal coronary sinus (PCS) near the coronary sinus ostium were simultaneously recorded at a paper speed of 150–250 mm/sec. During programmed ventricular extrastimulation and incremental ventricular pacing, ventriculoatrial conduction via the fast AV nodal pathway resulted in SRA activation before PCS, HRA and LRA activation. However, the sequence of retrograde atrial activation abruptly changed with a shift from retrograde fast to retrograde slow AV nodal pathway conduction. Characteristically, during ventriculoatrial conduction via the slow AV nodal pathway, activation of the PCS preceded SRA activation by 5–20 msec and was accompanied by an alteration of the temporal relationship between HRA and LRA activation in all patients. These observations suggest that anatomic, the proximal common AV nodal pathway is a broad area that permits the slow AV nodal pathway to have a retrograde exit located posteriorly, inferiorly and to the left of that of the fast AV nodal pathway, and that the retrograde atrial activation sequence recorded during tachyarrhythmias should be determined with caution while attempting to differentiate retrograde normal AV pathway from retrograde anomalous bypass tract conduction.

IN DIFFERENTIATING retrograde conduction via the normal atrioventricular (AV) pathway from an anomalous bypass tract, one must evaluate ventriculoatrial conduction properties during an electrophysiologic study.1-3 Ventriculoatrial conduction over the normal AV pathway is characterized by the earliest activation of the low septal right atrium (SRA) recorded in the His bundle electrographic lead and progressive prolongation of ventriculoatrial conduction time with increasing prematurity of ventricular extrastimulation. In contrast, ventriculoatrial conduction over an anomalous bypass tract has the earliest atrial activation at the site of its atrial insertion, and, characteristically, there is a lack of refractory-dependent ventriculoatrial conduction delay despite progressively premature ventricular extrastimulation.1-3 Dual AV nodal pathways are generally believed to be intranodal structures.4-8 Both fast and slow AV nodal pathways possess AV nodal properties with refractory-dependent conduction delay in both antegrade and retrograde directions.4-8 However, studies on the sequence of retrograde atrial activation have been limited to the fast AV nodal pathway.9,10 In the present study, we characterize and compare retrograde atrial activation sequences that result from ventriculoatrial conduction via the fast and the slow AV nodal pathways.

Materials and Methods

Electrophysiologic evidence of antegrade dual AV nodal pathway conduction was based on the induction of discontinuous AV nodal conduction curves (A1A2, H1H2) with programmed atrial extrastimulation,5,7 and retrograde dual AV nodal pathway conduction on the induction of discontinuous ventriculoatrial conduction curves (V1V2, A1A2) with programmed ventricular extrastimulation.5,7 Data from 19 patients with antegrade dual AV nodal pathways in whom multiple atrial electrograms were simultaneously recorded were analyzed. Seven of these patients also had retrograde dual AV nodal pathway conduction, which allowed comparative analysis of retrograde fast and retrograde slow AV nodal pathway conduction. These seven patients constituted the study population.

After the patients gave informed consent, all cardiotoxic and antiarrhythmic medications were discontinued 48–72 hours before the study. The study was performed with patients in a postabsorptive, nonsedated state. With a conventional technique,11 a tetrapolar electrode catheter (Elecath #5F) was introduced from the right femoral vein and placed in the right atrium across the tricuspid valve to record the His bundle potential (HBE), from which the SRA electrogram was recorded as well (fig. 1). To assure recording of the HBE, two pairs of electrodes with interelectrode distances of 1 mm and 10 mm, designated HBE1 and HBE2, were used. A hexapolar electrode catheter (USCI 004178 #7F) was introduced through an antecubital vein in the right arm. The distal pair of electrodes was placed at the right ventricular apex (RVA) for ventricular pacing, and the proximal two pairs of electrodes were placed in the right atrium to record high right atrial (HRA) and lateral right atrial (LRA) electrograms. The HRA...
and LRA electrographic leads had a recording interelectrode distance of 10 mm and were located 20 mm apart. During programmed atrial stimulation, the HRA lead was used for pacing and the LRA lead for recording. A tetrapolar electrode catheter (USCI 5675 #6F) was inserted from an antecubital vein in the left arm and placed in the coronary sinus (CS). The two pairs of electrodes of the CS catheter, designated CS$_1$ and CS$_2$, were adjusted under fluoroscope so that they were located underneath the HBE for recording CS atrial electrograms (CS$_1$ was believed to be at the CS ostium) (fig. 1). These two CS electrographic leads had a recording interelectrode distance of 10 mm and were located 10 mm apart.

Programmed atrial and ventricular stimulation consisted of extrastimulation and incremental pacing. During programmed extrastimulation, the HRA and the RVA endocardium were stimulated at one or two cycle lengths (CLs) (A$_1$A$_2$, or V$_1$V$_2$) with a programmed digital stimulator (Bioelectrotronix) that delivered 2-msec stimuli (S$_1$ and S$_2$) at approximately twice diastolic threshold. After every eighth paced beat (A$_1$ or V$_1$), a single premature atrial or ventricular beat (A$_2$ or V$_2$) was delivered at progressively shorter coupling intervals (A$_1$A$_2$ or V$_1$V$_2$) until the effective refractory period of the atrium or the ventricle was encountered.

Definition of Terms

AV and ventriculoatrial conduction intervals and refractory periods were defined and measured as conventionally described. A$_1$, H$_1$ and V$_1$ were SRA, His bundle and ventricular responses, induced by the driving stimuli (S$_1$). A$_2$, H$_2$ and V$_2$ were low SRA, His bundle and ventricular responses, induced by the premature stimuli (S$_2$).

When discontinuous AV nodal conduction curves (A$_1$A$_2$, H$_1$H$_2$) and discontinuous ventriculoatrial conduction curves (V$_1$V$_2$, A$_1$A$_2$) were induced during antegrade and retrograde conduction studies, the refractory periods of the fast and slow AV nodal pathways were measured and defined as described by Denes and Wu and co-workers. Briefly, the curve to the right of the discontinuity reflected the fast AV nodal pathway conduction and that to the left represented the slow AV nodal pathway conduction. In discontinuous A$_1$A$_2$, H$_1$H$_2$ curves, the longest A$_1$A$_2$ interval at which A$_2$ was blocked in the fast or slow AV nodal pathway was defined as the antegrade effective refractory period of the fast or slow AV nodal pathway. Similarly, in discontinuous V$_1$V$_2$, A$_1$A$_2$ curves, the longest V$_1$V$_2$ interval at which V$_2$ was blocked in the fast or slow AV nodal pathway was defined as the retrograde effective refractory period of the fast or slow AV nodal pathway.

Results

Antegrade Dual AV Nodal Pathway Conduction

At atrial driving CLs of 500–700 msec, discontinuous AV nodal conduction curves (A$_1$A$_2$, H$_1$H$_2$) suggestive of antegrade dual AV nodal pathway conduc-
tion could be induced with atrial extrastimulation in all seven patients (figs. 2 and 3). The antegrade effective and functional refractory periods of the fast AV nodal pathway ranged from 320-450 msec and from 410-580 msec, respectively. The antegrade effective and functional refractory periods of the slow AV nodal pathway ranged from <260-390 msec and from 460-550 msec, respectively (table 1). The atrial echo phenomenon was observed during antegrade slow AV nodal conduction in patients 4-6. However, only patient 6 had sustained AV nodal reentrant tachycardia of the slow-fast form, using the slow nodal pathway for antegrade conduction and the fast AV nodal pathway for retrograde conduction.

Retrograde Dual AV Nodal Pathway Conduction

At the same CLs chosen for atrial pacing, discontinuous ventriculoatrial conduction curves (V₁,V₂, A₁A₂) suggestive of retrograde dual AV nodal pathway conduction could be induced with ventricular extrastimulation in all patients (fig. 3B). The retrograde effective and functional refractory periods of the fast AV nodal pathway ranged from 320-450 msec and from 400-560 msec, respectively. The retrograde effective and functional refractory periods of the slow AV nodal pathway ranged from 220-300 msec and from 500-610 msec, respectively (table 1). Single ventricular echo phenomena could be induced during retrograde slow AV nodal pathway conduction in patients 1, 3, 4, 5 and 7. None of the patients had sustained AV nodal reentrant tachycardia of the fast-slow form.

Retrograde Atrial Activation Sequence

Simultaneous recordings of multiple atrial electrograms provided detailed analysis of retrograde atrial activation sequence during programmed ventricular stimulation in these patients. As would be expected, the sequence of retrograde atrial activation resulting from retrograde conduction over the fast AV nodal pathway was first the SRA in the HBE lead, followed by the proximal CS (CS₁ and CS₂), the HRA and the LRA in all patients. The SRA activation preceded proximal CS activation by 10-30 msec (table 2). In contrast, the retrograde atrial activation sequence resulting from retrograde conduction via the slow AV nodal pathway was characterized by earliest activation at the proximal CS. The activation of the proximal CS preceded low SRA activation by 5-20 msec and was accompanied by an alteration of the temporal relationship between LRA and HRA activation during ventriculoatrial conduction via the slow AV nodal pathway (table 2).

Figure 3B demonstrates the induction of discontinuous ventriculoatrial conduction curves (V₁,V₂, A₁A₂ and V₁,V₂, V₁A₂) with ventricular extrastimulation during right ventricular (RV) pacing at a CL of 650 msec. The retrograde effective and functional refractory periods of the fast AV nodal pathway were 350-360 and 400 msec, respectively, and the retrograde effective and functional refractory periods of the slow AV nodal pathway 290 and 610 msec, respectively. The ventricular echo zone coincided with the entire retrograde slow AV nodal pathway conduction curve. Retrograde slow AV nodal pathway conduction time (H₁A₂) was 280-320 msec.

Tracings corresponding to figure 3B are presented in figures 4 and 5. During RV pacing at a CL (S₁S₁) of 650 msec, a ventricular premature complex (S₂) at a premature coupling interval (S₁S₂) of 350 msec could be conducted to the atrium via either the fast or the slow AV nodal pathway (fig. 4). When the ventricular premature complex (S₂) was conducted by way of the fast AV nodal pathway, it lengthened ventriculoatrial conduction time (the S₂A₂ interval measured from the

![Figure 2](http://circ.ahajournals.org/)

**Figure 2.** Induction of antegrade dual atrioventricular (AV) nodal pathway conduction with atrial extrastimulation (case 1). The high right atrium is driven at a cycle length (S₁S₁) of 650 msec. (A) An atrial premature beat (S₂) at a premature coupling interval (S₁S₂) of 550 msec lengthens the AV nodal conduction time (AH) from 140 to 170 msec. (B) An atrial premature beat (S₂) at a premature coupling interval (S₁S₂) of 340 msec suddenly prolongs the AV nodal conduction time to 250 msec, resulting in discontinuous AV nodal conduction curves (A₁A₂, H₁H₂ and A₁A₂, A₂H₂) (fig. 3A). Paper speed = 150 mm/sec. LRA = lateral right atrial electrogram; CS₁ and CS₂ = coronary sinus leads. HBE = His bundle electrogram.
HBE lead) from 160 to 210 msec (fig. 4A). However, when the ventricular premature complex (S2) was conducted by way of the slow AV nodal pathway, it abruptly prolonged the ventriculoatrial conduction time (S2A2) to 440 msec (fig. 4B), thereby producing discontinuous ventriculoatrial conduction curves (V1V2, A1A2 and V1V2, V2A2) (fig. 3B). This was attributed to failure of retrograde fast with resultant retrograde slow AV nodal pathway conduction. A ventricular echo phenomenon was initiated (fig. 4B). Progressive shortening of the ventricular premature coupling interval (S2S3) continued to induce retrograde slow AV nodal pathway conduction with the ventricular echo phenomenon (fig. 5A) until ventriculoatrial conduction failed at a ventricular premature coupling interval (S3S4) of 290 msec (fig. 5B). The retrograde His bundle potential (H-) was recorded. Retrograde AV nodal conduction time (H-A) was 80 msec for the fast AV nodal pathway (fig. 4A) and 310-320 msec for the slow AV nodal pathway (figs. 4B and 5A).

The sequence of retrograde atrial activation was analyzed with measurements of ventriculoatrial conduction time (S2A2) at each atrial recording site. During retrograde fast AV nodal pathway conduction, the SRA in the HBE lead was activated 20-30, 40 and 60 msec before CS1 and CS2, the HRA and the LRA, respectively (fig. 4A). In contrast, during retrograde

![Diagram](http://circ.ahajournals.org/lookup/doi/10.1161/01.CIR.64.5.1062)

**Table 1. Electrophysiologic Data**

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<th>Pt</th>
<th>DCL (msec)</th>
<th>FP (msec)</th>
<th>SP (msec)</th>
<th>AERP FP (msec)</th>
<th>AERP SP (msec)</th>
<th>Atrial echo zone (msec)</th>
<th>RERP FP (msec)</th>
<th>RERP SP (msec)</th>
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**Abbreviations:** AERP = antegrade effective refractory period; AFPR = antegrade functional refractory period; DCL = driving cycle length; FP = fast atrioventricular nodal pathway; RERP = retrograde effective refractory period; RFRP = retrograde functional refractory period; SP = slow atrioventricular nodal pathway.
TABLE 2. Temporal Relationship of Atrial Electrograms During Retrograde Dual Atrioventricular Nodal Pathway Conduction

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<th>Pt</th>
<th>SRA (msec)</th>
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<th>LRA (msec)</th>
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</table>

The numbers indicate msec after the earliest activation site, which is designated as the zero reference point.

Abbreviations: CS = coronary sinus; FP = fast atrioventricular nodal pathway; HRA = high right atrium; LRA = lateral right atrium; PCS = proximal coronary sinus; SP = slow atrioventricular nodal pathway; SRA = low septal right atrium.

slow AV nodal pathway conduction, the sequence of retrograde atrial activation was abruptly changed. The CS1 and CS2 were activated 5–10, 25 and 40 msec before the SRA, the LRA and the HRA, respectively (figs. 4B and 5A). The change in the temporal relationship of retrograde atrial activation occurred not only between the SRA and CS1 and CS2, but also between the HRA and the LRA. Further, the change in the retrograde atrial activation sequence consequent upon the shift from retrograde fast to retrograde slow AV nodal pathway conduction was accompanied by alterations of the morphology of the atrial electrograms (figs. 4 and 5).

The sequence of retrograde atrial activation resulting from each AV nodal pathway conduction in the retrograde direction was consistently reproducible with repeated ventricular extrastimulation. The characteristic alteration of the retrograde atrial activation sequence consequent upon the shift from retrograde fast to retrograde slow AV nodal pathway conduction could also be observed during ventriculoatrial Wenckebach phenomenon induced by rapid ventricular pacing in all patients. One example is given in figure 6. The right ventricle was driven at a CL of 540 msec, which induced 4:3 ventriculoatrial Wenckebach phenomenon. Ventriculoatrial conduction time cor-

![Figure 4](http://circ.ahajournals.org)
Figure 5. Further shortening of the ventricular premature coupling interval (S1S2) continues to induce ventriculoatrial conduction by way of retrograde slow atrioventricular (AV) nodal pathway conduction (A) until ventriculoatrial conduction fails at the ventricular premature coupling interval (S1S2) of 290 msec (B). Note that the retrograde atrial activation sequence and the morphology of the atrial electrograms resulting from retrograde slow AV nodal pathway conduction are different from those by way of retrograde fast AV nodal pathway conduction during basic driving beats (S1). Retrograde slow AV nodal pathway conduction time (H-A) measures 320 msec. Paper speed = 250 mm/sec. HRA = high right atrium; LRA = lateral right atrium; CS1 and CS2 = coronary sinus leads; HBE1 and HBE2 = His bundle electrogram.

Figure 6. Four-to-three ventriculoatrial Wenckebach phenomenon induced by rapid ventricular pacing at a cycle length of 540 msec (case 1). The ventriculoatrial conduction time (SA interval) is measured from the stimulus (S) to the onset of atrial electrogram at each recording site and is expressed in msec. Note sudden prolongation of ventriculoatrial conduction time after the second paced beat, suggestive of failure of retrograde fast atrioventricular (AV) nodal pathway with resultant retrograde slow AV nodal pathway conduction. The retrograde atrial activation sequence resulting from retrograde fast AV nodal pathway conduction (corresponding to the first paced beat) and that resulting from retrograde slow AV nodal pathway conduction (corresponding to the second and third paced beats) were similar to those induced with programmed ventricular extrastimulation (figs. 4 and 5). These findings were consistently reproducible with
repeated rapid ventricular pacing in all patients. An additional example (patient 5) is shown in figure 7.

**Discussion**

Observations made in this study indicated characteristic alteration of the retrograde atrial activation sequence resulting from a shift from retrograde fast to retrograde slow AV nodal pathway conduction in patients with dual AV nodal pathways. In previous studies, either only HRA and SRA electrograms were recorded for analysis of the sequence of retrograde atrial activation or the description of retrograde atrial activation sequence was limited to that resulting from retrograde fast AV nodal pathway conduction. The present study, therefore, provides further information pertaining to the understanding of retrograde dual AV nodal pathway conduction.

The induction of discontinuous AV nodal conduction curves (A1A2, H1H2) with atrial extrastimulation conformed to the presence of antegrade dual AV nodal pathways (fig. 3A, table 1). Nevertheless, the induction of discontinuous ventriculoatrial conduction curves (V1V2, A1A2) with ventricular extrastimulation would also raise the possibility of coexisting anomalous bypass tracts functioning in the retrograde direction. It has been described that discontinuous ventriculoatrial conduction curves (V1V2, A1A2) can be induced with ventricular extrastimulation during retrograde conduction over the normal AV pathway and an anomalous bypass tract when either of the two fails to conduct in the retrograde direction. Analysis of discontinuous ventriculoatrial conduction curves (V1V2, A1A2) induced in our patients revealed that both fast and slow pathways exhibited AV nodal conduction properties during retrograde conduction, with the fast pathway having a retrograde effective refractory period longer than that of the slow pathway (fig. 3B, table 1). Also, despite having different sequences of retrograde atrial activation, the earliest sites of retrograde atrial activation resulting from retrograde conduction over the two pathways, the SRA and CS1, were anatomically close to the AV septum (fig. 1). Klein et al. recently observed decremental retrograde conduction via anomalous bypass tracts in three of their 30 patients with the Wolff-Parkinson-White syndrome. However, the magnitude of conduction delay during retrograde conduction over the slow pathway as demonstrated in this study was much greater than that reported by Klein et al., as evidenced by recordings of atrial electrograms far apart from those of ventricular electrograms during retrograde slow pathway conduction (ventriculoatrial intervals ranging from 290–525 msec) (figs. 4–6). These observations show that the slow pathway has characteristics of the AV node in the retrograde direction in these patients.

The structural and cellular complexity of the human AV junctional area has not been completely clarified and the definition of the AV node has created considerable controversies. In the isolated rabbit heart, Paes de Carvalho and de Almeida distinguished three functional separate parts in the AV node based on different action potential recordings: atrialnodal, nodal and nodo-His zones. These three cell zones were subsequently found to correlate to some extent with the three cell types (transitional, upper nodal and lower nodal) described in the histologic studies performed by Anderson. The precise location of dual AV nodal pathways in relation to the AV nodal structure, however, is speculative. In isolated rabbit hearts, Janse et al. demonstrated dual AV nodal inputs and induction of atrial echo phenomenon with atrial extrastimulation. Unfortunately, they could not completely map out the AV nodal reentrant circuit and suggested that many possible different pathways might exist within the AV node.

Our findings indicate that the proximal common
AV nodal pathway is anatomically a broad area permitting the slow AV nodal pathway to have a retrograde exit located posteriorly, inferiorly and to the left of that of the fast AV nodal pathway (fig. 8). This is in keeping with the findings made by Spach et al., in which wave fronts resulting from His bundle pacing rapidly propagated into the anterior part of the AV node and then slowly penetrated the middle and posterior parts of the AV node toward the coronary sinus in isolated canine and rabbit hearts. These observations support the concept that the atrium may not be a necessary link for AV nodal reentry and imply that the presence of dual AV nodal pathways may be both functional and anatomic.

Recording the retrograde sequence of atrial activation using the standard technique of intracardiac recordings has limitations. First, it is difficult to maintain the proximal CS catheter electrodes close to the HBE catheter electrodes (fig. 1). Cardiac movements associated with programmed electrical stimulation can easily displace the catheter electrodes. Therefore, the position of the CS catheter electrodes must be readjusted during the study. Second, the extent of alteration in the retrograde atrial activation sequence so recorded may depend on anatomic variation of the size and location of the AV node as well as the magnitude of conduction delay related to retrograde slow AV nodal pathway conduction. It appears that the longer the retrograde slow AV nodal pathway conduction time, the more likely the change in the retrograde atrial activation sequence. Third, some catheter electrode movement during cardiac systole and diastole is expected, particularly when associated with changes in the cardiac CL may account for some of the findings, although we could consistently reproduce the findings in our patients.

Electrophysiologic Implications

Our electrophysiologic findings may be relevant to the understanding of what causes the permanent form (or the fast-slow form) of AV junctional reciprocating tachycardia with an RP interval longer than the PR interval. A critical question has been raised as to whether the anatomic substrate of the retrograde limb of the tachycardia circuit is an intranodal or an extranodal structure. Theoretically, perpetuation of the ventricular echo phenomenon using the slow pathway for retrograde conduction and the fast pathway for antegrade conduction can lead to the fast-slow form of AV junctional reciprocating tachycardia in five of our seven patients (figs. 4B and 5A) (table 1). The magnitude of conduction delay and the sequence of retrograde atrial activation resulting from retrograde slow pathway conduction presented herein are similar to those from retrograde conduction via the retrograde limb of the fast-slow form of AV junctional reciprocating tachycardia recently described. With induction of the atrial preexcitation phenomenon when the His bundle is refractory during tachycardia, several investigators believe that the retrograde limb of the fast-slow form AV junctional reciprocating tachycardia is an anomalous bypass tract with AV nodal properties. Under this circumstance, however, one cannot exclude the presence of a retrograde conducting nodoventricular bypass tract bridging the slow AV nodal pathway and the ventricle. Anderson et al. suggest that anatomically, there are two types of nodoventricular bypass tracts: One connects the anterior part (Mahaim fibers) and the other the posterior part (Paladino fibers) of the AV node to the ventricle. It is tempting to postulate that the latter type of nodoventricular bypass tract (Paladino fiber), capable only of retrograde conduction, is the anatomic substrate of the retrograde limb of the fast-slow form AV junctional reciprocating tachycardia.

We recently observed that the fast-slow form of AV junctional reciprocating tachycardia may remain sustained after development of AV block in certain patients (Sung RJ: personal observation). This observation suggests that the ventricle is not a necessary link of the tachycardia circuit and is thus in favor of the theory that reentry occurs within the AV node or involves double AV nodes in these patients. The presence of double AV nodes has been well documented, although their prevalence and functional significance are not known. Nevertheless, we must also consider observations made by other investigators in which involvement of an anomalous

![Figure 8](http://circ.ahajournals.org/)

**Figure 8.** Schematic representation of retrograde dual atrioventricular (AV) nodal pathway conduction. The coronary sinus (CS) ostium is located posterior and inferior to the AV node. (left) Retrograde fast AV nodal pathway conduction. (middle) Retrograde slow AV nodal pathway conduction. (right) Retrograde slow AV nodal pathway conduction with a ventricular echo phenomenon. It is suggested that the slow AV nodal pathway has a retrograde exit site located posterior and inferior to that of the fast AV nodal pathway. A = atrium; H = His bundle; V = ventricle; FP = fast AV nodal pathway; SP = slow AV nodal pathway.
bypass tract has been implicated. Various anatomic substrates may be responsible for the fast-slow form of AV junctional reciprocating tachycardia. Further anatomic studies are necessary to substantiate these theories.

References
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