The study of atrioventricular bypass tracts remains an educational cornerstone for students of electrophysiology seeking to understand the principles of reentry, mapping, tachycardia mechanism diagnosis in the electrophysiology laboratory, and ablation. Surgical and subsequently catheter ablation procedures to eliminate these tracts derived from an understanding of their anatomic location, typically bridging the atrioventricular annulus allowing conduction from atrium to ventricle to bypass the normal atrioventricular node. With this appreciation of anatomy and physiology, pacing maneuvers can be applied and interpreted to clarify the presence and electrophysiological properties of atrioventricular bypass tracts in the electrophysiology laboratory.

In this segment of Teaching Points in Electrophysiology, Patel and colleagues present and carefully examine a different type of bypass tract, one connecting the right atrium to a pulmonary vein (PV) bypassing the left atrial myocardium. The underlying principle for PV isolation derives from the construct that the PV myocardium is solely activated via conduction from the left atrial myocardium across the PV ostium. The presence of an intercaval bundle creating a tract that electrically connects the posterior right atrium and the anterior aspect of the right superior PV makes isolation of this vein with left atrial ablation alone impossible.

Similar tracts may also bypass the left atrium and connect a left PV to the coronary sinus (CS) musculature, to the left atrial appendage (LAA), or to an adjacent left PV. In the latter case, ostial encircling ablation lines will fail to isolate the vein. In the former 2 cases, even encircling antral ablation lines around the left PVs may fail to isolate these structures. In some patients, the remnant of the left superior vena cava—the ligament and vein of Marshall (VOM)—serves as the tract connecting the CS myocardium to a PV. The presence of these tracts has important implications. Because exit block cannot be achieved with left atrial ablation alone, the arrhythmogenic substrate within the vein remains and is capable of triggering atrial fibrillation. In addition, these tracts may participate in reentry and can produce complex reentry paths. In the case of the epicardially located VOM, the tract does not connect only to the CS and PV, but in its course as one of the oblique veins of the left atrium, it can connect to multiple sites on the left atrial epicardial wall, resulting in a complex reentry substrate. Occasionally, a large macroreentrant circuit involving Bachmann’s bundle, the right and left atria, the ostial LAA myocardium, the VOM, and the CS myocardium may occur, particularly in patients with prior atrial surgery.

The tract itself can also supply the trigger for atrial fibrillation. The myocardial sleeves surrounding the VOM are similar to those around the PVs and within the CS and may give rise to premature atrial contractions triggering atrial tachycardia and atrial fibrillation.

**Diagnosis and Ablation of Anomalous PV Connections**

**Confirming PV Activation**

The first step is to show that potentials recorded from the vein are not produced by adjacent structures (eg, the LAA when recording from the left PVs), by showing that pacing within the PV does capture the local PV myocardium. The next step is to demonstrate that the earliest PV signal is not at the ostium, but within the vein. Without bypass tracts, the left atrium is the source for PV activation, and PV signals are earliest at the ostium and become progressively later as the catheter is moved deeper into the vein. With a bypass tract that inserts distal to the ostium, the antrum is activated later than the more distal PV tissue.

**VOM Connections**

**High and Low Output Pacing in the CS for VOM Connections**

High output pacing in the CS proximal to the VOM captures left atrium and CS myocardium, but at low output may capture only the CS myocardium. If there is no change in the timing of the PV potential between high and low output pacing (with CS and LA capture compared with capture of the CS alone) then a bypass tract is present and depends only on the CS myocardium to activate the PV myocardium via the VOM.

Pacing within the VOM will pull in the PV signals, activating them earlier, whereas pacing at other sites outside the PV (eg, the LAA) fails to do so.

Ablation of the VOM tissue or all of its connection can be difficult, but may be achieved by a variety of approaches:

1. Transmural ablation at the endocardial ridge anterior to the left PVs.

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2. Ablation within the VOM by selective cannulation of the VOM via the CS.
3. Alcohol ablation of the VOM with selective cannulation via the CS.
4. Epicardial ablation by placing the catheter within the transverse sinus and then pulling back along the course of the VOM in the sulcus between the LAA and PVs.\textsuperscript{2,3}

PV to PV Bypass Tracts
Myocardial bridges distal to the ostium that occur between individual PVs are particularly likely to occur when a narrow common ostium is present with later branching between the 2 PVs.\textsuperscript{4,5} When wide area circumferential ablation is done and both ipsilateral veins are isolated simultaneously, these bypass tracts are irrelevant. However, when individual PV isolation is done, then persistent PV conduction may occur through one of these tracts. Pacing in the ipsilateral vein will pull in the signals that remain in the vein that is already encircled with ablation lesions. Care must be taken to avoid direct capture of the adjacent vein by pacing in the ipsilateral vein on the side facing away from the vein being mapped. For example, if left upper vein isolation is failing to achieve entrance block, then pacing is performed in the left lower vein on its inferior wall.

LAA to Left PV Tracts
The VOM and left superior vena cava sulcus creates a plane of separation between the posterior wall of the LAA and the anterior wall of the left PVs. Some patients have myocardial connections that bridge this sulcus and diagnosis can be difficult. When this occurs, delineation of far-field signals arising from the LAA cannot be demonstrated in the usual manner by pacing in the LAA because the direct connection will cause the PV potentials to be pulled. In patients who have had a LAA closure device placed, pacing maneuvers may not be possible from within the LAA.

Confirming the Diagnosis
1. Depending on where these bypass tracts occur, the earliest PV activation is at that site distal to the ostium.
2. Pacing on the anterior wall of the LAA will pull in the PV signals with the same activation sequence.
3. Pacing on the posterior wall of the left PV will cause early activation within the LAA.

Ablation
1. During pacing of the left PV posteriorly, an activation map of the LAA can be created and the earliest site of activation targeted for ablation energy delivery.
2. If the LAA has been occluded with an endocardial device, circumferential isolation around the device of the LAA may be necessary to isolate the left PVs.

Right Atrium/Superior Vena Cava to Right PV Bypass
Patel and colleagues\textsuperscript{1} elegantly describe a set of patients where targeted mapping and ablation of fibers that bypass the left atrial ostium and directly connect the anterior wall of the right PVs to the right atrium or superior vena cava. These tracts are perhaps the best recognized of those described in this perspective.\textsuperscript{4,6} In addition to the inability to isolate the vein, these bypass tracts may constitute a limb of a reentrant circuit that involves the right atrium, left atrium, and the right-sided PVs when a gap in the encircling PV line is present. When slow conduction is present related to this gap, the tachycardias may be easily induced or incessant. Re-isolation of the vein or ablation at the right atrial entrance site for the bypass tract will terminate the macroreentrant tachycardia, but for isolation of the vein, both the left atrial gap and bypass tract must be eliminated.

Confirming the Diagnosis
1. Mapping within the PV will verify that the early site of PV activation is within the vein rather than at the ostium.
2. Because the far-field signal seen in the right veins is the right atrium (rather than solely the left atrium) pacing the right atrium in the absence of a bypass tract will typically pull in the far-field signal, but the near-field PV signal will remain unchanged. When a bypass tract is present, pacing the right atrium will pull in both the near-field and far-field signals. The operator may incorrectly assume that no PV potentials (only far-field signals) are seen, and the vein is already isolated. However, pacing in the PV itself will capture and verify that onset of the signals is indeed PV in origin, and thus a bypass tract is the reason for the unusual RA pacing response.
3. Care must be taken when pacing in the right atrium that the site of stimulation is not exactly adjacent to the PV to avoid direct capture of the PV.

Ablation
Patel and colleagues\textsuperscript{1} clearly delineate an approach to managing this type of bypass tract when it occurs. Although presumably some tracts may insert close to the ostium and can be at least temporarily eliminated with ostial ablation, the technique most likely to be successful is to pace the posterior wall of the right PV and map the right atrium to identify the exit site to the right atrium which can then be targeted for ablation. Patel and colleagues\textsuperscript{1} should be congratulated on pursuing in a logical and iterative manner the cause for the apparent reconnection of the right PVs seen in their patients. Although atrioventricular bypass tracts are perhaps the classic entity from which we have learned the principles of mapping and ablation, these new bypass tracts also require the application of electrophysiological principles to recognize these as a cause of apparent failure to isolate a PV or as a cause of reentry.

Disclosures
Dr Asirvatham receives no significant honoraria and is a consultant with Abiomed, Atricure, Biosense Webster, Biotronik, Boston Scientific, Medtronic, Spectranetics, St. Jude, Sanofi-Aventis, Wolters Kluwer, Elsevier. Dr Stevenson is coholder of a patent on needle ablation that is consigned to Brigham and Women’s Hospital.

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