Fascicular Ventricular Arrhythmias
Pathophysiologic Mechanisms, Anatomical Constructs,
and Advances in Approaches to Management

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Ventricular arrhythmias involving the fascicular system may be seen in both structurally normal and abnormal hearts. Idiopathic fascicular ventricular tachycardia represents almost 10% to 15% of idiopathic ventricular tachycardia related to the left ventricle. Cohen et al1 and subsequently Zipes et al4 first described these arrhythmias in the 1970s as relatively narrow right bundle left axis arrhythmias that arose close to the posterior fascicle and could be induced with atrial pacing. Bébhiassen et al3 later described the responsiveness of these arrhythmias to verapamil. Although initial studies focused on arrhythmias related to the left posterior fascicle, it is possible for arrhythmias to arise from any portion of the fascicular system and in both structurally normal and abnormal hearts. Furthermore, when approaching the patient presenting with arrhythmias arising from the His-Purkinje system, it is important to consider the unique complexities related to mapping and ablation. In this review, we will focus on the mechanisms of such arrhythmias, relevant embryology, anatomy and physiology, and approaches to management in both the presence and absence of other structural heart disease. Broadly, fascicular ventricular tachycardia in the absence of other structural heart disease will be termed idiopathic fascicular ventricular tachycardia (IFVT), whereas that related to structural disease will be discussed in the context of the relevant disease state.

Generally, IFVT is separated into 3 types—left posterior fascicular with a right bundle branch block pattern and left axis deviation, left anterior with a right bundle branch block and right axis deviation pattern, and left upper septal fascicular with a narrow QRS and normal axis but often with a right bundle branch block morphology. There are rare reported cases of left bundle branch block pattern, V1–V6 transition IFVT with a normal axis arising from the right bundle branch. In addition, we will touch on other Purkinje- and fascicular-related arrhythmias because they relate in diagnosis and mapping to IFVT. However, by far, the most common form of IFVT is the posterior fascicular type (=90% of cases) (Table 1). We will exclude consideration of premature ventricular contraction–triggered ventricular fibrillation that may similarly involve abnormalities in the His-Purkinje system from this review.

Electrophysiological and Anatomical Characteristics

In ablation of fascicular ventricular arrhythmias, an understanding of the normal anatomical course of the fascicles is critical. However, variation in the anatomical course is common. In the normal human heart, the penetrating bundle of His arises from the atrioventricular node and runs in the central fibrous body as a cord-like structure, typically dividing into the left and right bundles at the junction of the membranous septum and the crest of the muscular interventricular septum. The right bundle then arises at an obtuse angle with the distal third of the right bundle being more superficial and coursing to the right ventricular free wall in the moderator band. The left bundle tends to be broader than the right bundle and emerges just beneath the noncoronary cusp of the aortic valve, giving rise to a thinner anterior fascicle and broader posterior fascicle. Almost 60% of people may also have a third fascicle termed the left septal, upper, or median fascicle.7,8 The left bundle anatomy can exhibit considerable variation in the normal heart with potential for significant cross-linking between fascicles and variability in the width, length, and degree of arborization (Figure 1). The fascicular system ultimately terminates in a mesh-like Purkinje network. The Purkinje fibers vary in density throughout the heart, largely seen around the papillary muscles and midventricle, and less so at the base of the heart. Furthermore, they can penetrate as deep as a third of the myocardial thickness.10,11

Functionally, the electrophysiological tendency for the fascicular–Purkinje system to participate in tachycardia may be because of the unique physiology that allows the system to overcome source–sink mismatch.15 On the basis of all existing data, electrical propagation from Purkinje to ventricular myocyte depends on direct charge transfer. Thus, transmission at the Purkinje–myocyte junction always has the potential to be bidirectional (ie, anterograde and retrograde). In fact, given the larger ventricular mass, the potential for retrograde activation may actually be higher than anterograde activation. This has been demonstrated by work done by Joyner et al.14,15 One...
mechanism by which retrograde activation is prevented is best understood by the gating hypothesis proposed by Myerburg et al.,\(^\text{16}\) wherein the action potential duration increases as one moves distally from the point of initial stimulus, thus resulting in the region of greatest refractoriness being at the distal 2 to 3 mm of the Purkinje fiber, which as a result serves as a gate against retrograde conduction. However, during every conducted beat, not all Purkinje–myocyte junctions are activated, with quiescent junctions existing among activated junctions that may be later recruited based on cycle variability of anterogradely conducted signals.\(^\text{12}\) Thus, although certain protective mechanisms may exist within the Purkinje–myocyte junction to prevent retrograde propagation, the potential for retrograde activation still exists and may further explain why reentry may occur in otherwise normal ventricular and Purkinje myocardium.

### Embryological Considerations

The bundle of His and Purkinje cells have distinct embryological origins, which may underlie potential arrhythmogenicity. Although the bundle of His develops from a cluster of periodic acid–Schiff positive cells around the primitive atrioventricular node, which then travel down the septal ridge to form the bundle branches, the Purkinje cells are derived from contractile cardiac myocytes and embryonic ventricular cells.\(^\text{17,18}\) Once the bundle of His and ventricular trabeculae consisting of Purkinje cells have, respectively, developed on day 11 to 12 of embryogenesis, both structures connect to one another to complete the formation of the primary ventricular conduction system.\(^\text{19}\) One limitation in modeling an embryologic basis for IFVT is the great interspecies variability both in anatomical distribution and in number of Purkinje fibers.\(^\text{12}\) However, given the different embryological origins and interfacing that occurs late in embryogenesis, the potential for myocardial disarray during this complex period of development may partly contribute to arrhythmogenesis. Furthermore, although genetic factors may increase the arrhythmogenic potential of Purkinje fibers, specific relationship to the pathogenesis of IFVT has not been well characterized.\(^\text{20}\)

### Pathophysiologic Mechanisms of Fascicular Ventricular Tachycardia

#### Automatic Versus Reentrant

Initial studies suggested automaticity as the mechanism of fascicular ventricular arrhythmias, especially given association with exercise, the ability to induce with burst pacing, and characteristics of the His-Purkinje system that could confer the potential for both normal and abnormal automaticity.\(^\text{21}\) For example, in the setting of digoxin toxicity, the mechanism of ventricular tachycardia (VT) is thought to be enhanced automaticity in the region of the fascicles. However, the majority of studies have laid more weight on there being a reentrant basis for IFVT.\(^\text{21–23}\) VT that appears morphologically similar to IFVT but exhibits features more suggestive of automaticity may be more consistent with focal Purkinje VT.\(^\text{24}\)
The reentrant theory suggests that IFVT is the result of a calcium-dependent circuit because of abnormal Purkinje fiber conduction. In this setting, the reentrant zone is thought to involve retrogradely activated fast conduction fibers during tachycardia along with antegrade conduction through a verapamil-sensitive zone. Ouyang et al elegantly demonstrated this association, with unidirectional block and resulting macroreentry within the Purkinje network subtending arrhythmia initiation. Although it is fairly consistent that the upper turnaround of the reentrant circuit is likely located near the His or proximal left bundle/fascicle area, the retrograde limb of the circuit may vary from patient to patient. Previous studies have also suggested the role of a fibromuscular false tendon in the pathophysiology of fascicular VT as ablation of this tendon has led to elimination of the reentrant form of IFVT in several cases. Further supporting reentry is the ability to entrain with ventricular and atrial pacing, with the use of the latter supporting involvement of the fascicles given the easy access over the conduction system into the reentry circuit. However, it is possible that in some cases of apparent IFVT, the fascicle may act as a bystander with the retrograde limb comprising the left ventricular myocardium. Thus, it may be important to also recognize the contribution of false tendons or other structures in arrhythmogenesis.

Role for the False Tendon?
Many of the studies concerning IFVT occurred before the widespread use of intracardiac echocardiography (ICE). The suggestion that a false tendon may underlie the pathophysiology of IFVT in some patients has been supported by several investigators. The false tendons are thought to be noncompacted extensions of the His-Purkinje system and are electrophysiologically active. Pathologically, they have been shown to contain Purkinje fibers and that their electric properties (action potential duration and refractory period) vary with changes in the degree of length–tension application. Furthermore, there is a significant association between the incidence of false tendons on echocardiography and that of idiopathic left ventricular tachycardia. Perry et al reported a 0.8% overall incidence of false tendons in a group of 3847 patients, although 37% of those with false tendons had exercise-associated premature ventricular contractions. The false tendon as a mechanism for macroreentry, given different conduction characteristics from the remaining myocardium, makes physiological sense. However, close attention to imaging (transthoracic echocardiography, ICE, and magnetic resonance imaging) may be necessary to identify these structures in patients presenting with IFVT.

Figure 2. An example of a patient with incessant ventricular tachycardia, which was thought to arise near the left anterior fascicle. However, mapping along the false tendon demonstrated mid-diastolic potentials (top left—potentials labeled). The intracardiac echocardiography (ICE) image (right) demonstrated contact of the distal tip with the tendon. The bottom left image depicts entrainment at this site along the false tendon, where ablation was successful in terminating tachycardia. See Movie I in the Data Supplement for ICE video.
Structurally Normal Versus Structurally Abnormal Hearts With VT Suggesting Fascicular Involvement

Fascicular VT can occur in both structurally normal and abnormal hearts. Arrhythmias related to the His-Purkinje system in structurally abnormal or ischemic hearts are often caused by Purkinje fibers with abnormal automaticity. In the setting of structural heart disease (in particular infarct or nonischemic involvement of the septum), changes in health of components of the His-Purkinje system may also lead to unidirectional block in one component of the fascicular system and resulting interfascicular or bundle branch reentry that may appear as IFVT on the basis of 12-lead electrocardiography. One way to distinguish VT attributable to the presence of structural heart disease from idiopathic causes is the RS interval, with fascicular VT generally demonstrating an RS interval <80 ms in all precordial leads.

Electrocardiographic Differentiation of Fascicular From Other Arrhythmias

Fascicular ventricular arrhythmias are commonly narrow (ie, 110–140 ms in QRS duration) and have typical morphological characteristics on 12-lead electrocardiography. Generally, arrhythmias arising from a specific fascicle will have a QRS morphology similar to that seen in sinus rhythm with block in the remaining portions of the His-Purkinje system (eg, IFVT arising from the posterior fascicle may have a representative right bundle branch block/left anterior deviation-type morphology). However, this need not always be the case because of arborization of the distal Purkinje fibers resulting in opportunity for varying QRS morphology dependent on the exact path of distal myocardial activation. This phenomenon is similar to that seen with papillary muscle-related or other VT where a focus that is insulated from the rest of the myocardium may have variable exits (and thus the exact site of earliest myocardial exit may not reflect the arrhythmia source).

When reviewing the ECG of a patient presenting with possible fascicular VT, it is important to not confuse the arrhythmia with supraventricular tachycardia with aberrancy. Evidence of ventriculo-atrial dissociation is one useful characteristic but is not always present, especially in younger patients. Furthermore, at the time of the electrophysiology study, initial induction of a supraventricular tachycardia should not immediately rule out possible IFVT given that as many as 10% to 25% of patients with IFVT may also have supraventricular tachycardia. It is important to note that one key method of differentiating the two is by comparing H-V intervals during sinus rhythm versus tachycardia (see below).

Two arrhythmias that may commonly be confused with IFVT are arrhythmias arising from the papillary muscles and arrhythmias arising from the mitral annulus. This is because of the relatively small anatomical area that separates these structures. The role of a mismatch in conduction characteristics between fascicular, Purkinje, and myocardial tissue in the pathogenesis of IFVT has also been described in papillary muscle ventricular arrhythmias, in which Purkinje fibers that penetrate deep into the tissue have been implicated in the source–sink mismatch responsible for arrhythmogenesis. Several authors have published criteria to differentiate specifically left posterior fascicular VT from ventricular arrhythmias arising from the posteromedial papillary muscle. However, it is important to recognize that electrocardiographic distinction between these arrhythmias is artificial. Specifically, Purkinje and fascicular tissue exist on the papillary muscle and components of the papillary muscle may arise on the septum close to where the conduction system normally transitions from fascicle to Purkinje tissue. Furthermore, Purkinje tissue and remnant Purkinje-like tissue may exist in many areas of the heart, including the outflow tracts, papillary muscles, and close to the mitral annulus. Thus, attempts to identify distinguishing electrocardiographic characteristics must be considered in the context of normal anatomical variability of fascicular, Purkinje, and papillary muscle tissue. Thus, although electrocardiographic criteria may be useful, recognizing its limitations is important as well.

Pharmacological Management Options

In cases of IFVT, verapamil has proven a mainstay of therapy (thus the term verapamil-sensitive idiopathic left ventricular tachycardia). The mechanism of action of verapamil is via the slow inward calcium channel. Unfortunately, chronic treatment with oral verapamil is not as effective as acute treatment with intravenous verapamil. Propranolol has also been proposed as an effective treatment. Generally, fascicular VT does not respond to adenosine, although case reports have been published suggesting rare responsiveness. Although use of drug therapy may be useful, ablation, particularly in IFVT, has been suggested to have a high success rate (as high as 80%).

Pre- and Intraprocedural Set-Up

The approach to mapping and ablation of any arrhythmia relies on 3 principles: preoperative recognition of the arrhythmia and presumptive substrate; ability to induce the arrhythmia at the time of invasive mapping; and appropriate mapping of the relevant signals with targeted ablation. Fascicular ventricular arrhythmias comprise a unique problem for several reasons: (1) the substrate is often normal macroscopically and, thus, traditional methods of substrate mapping used in other scar-related arrhythmias may not be applicable; (2) earliest myocardial activation does not necessarily indicate arrhythmia source; and (3) variable anatomy and degree of endocardial penetration of the fascicle and relevant Purkinje fibers may make typical mapping and ablation techniques technically difficult. Thus, a systematic approach to preoperative recognition, induction, mapping, and ablation is critical.

Substrate Considerations

An important consideration is whether or not the heart is truly structurally normal. In the presence of previous infarct, Purkinje-related VT is not uncommon and may present with similar rapid upstroke to that of fascicular VT. However, sometimes substrate may not necessarily be obvious via traditional imaging methods such as echocardiography and may not be sufficiently extensive to cause a decrease in ejection fraction. In a recent study, magnetic resonance imaging in patients presenting with fascicular VT and preserved ejection fractions demonstrated total absence of delayed enhancement in only 4 out of 9 patients. Among the remaining patients, either unifocal or multifocal fibrosis was identified and was associated
with the sites of successful ablation of IFVT. Thus, it is possible that some patients with apparently normal cardiac function and IFVT may, in fact, have corresponding substrate. Whether there is a threshold in terms of degree of substrate needed to confer an increased risk of VT recurrence or whether the presence of fibrosis signifies a progressive process (eg, sarcoidosis) or a fixed substrate from a previous subclinical event (eg, myocarditis) is unknown. and further study is required. The relevance to mapping, however, lays in that the recognition of pre-existing substrate that may offer an approach to mapping a potentially targetable fixed substrate even if the arrhythmia is noninducible.

Induction at Electrophysiology Study
As with any electrophysiological procedure, induction of the arrhythmia at the time of ablation is critical to mapping. However, dependence on sympathetic activity and effects of sedation and subcutaneous lidocaine on inducibility may make induction difficult. Reports have suggested that VT may be noninducible in as many as 25% to 40% of cases. Gopi et al published a stepwise approach to inducing IFVT. In addition, preoperative cessation of antiarrhythmics, β-blockers, and calcium channel blockers at least 3 half-lives before the procedure is important.

Considerations in Mapping
An array of modalities may be used when mapping fascicular VT. However, use of fluoroscopy, ICE, and an electroanatomic mapping system may help optimize the likelihood of success. Although fluoroscopy has been most traditionally used, and the skilled electrophysiologist can make excellent anatomical determinations with fluoroscopy alone, it lacks fine definition (in particular for endocavitary structures, catheter contact, etc) that ICE has. As a result, modern-day diagnostic strategies have shifted focus toward greater utilization of ICE.

Approach to Mapping
Ideally, induction and maintenance of tachycardia will best assist the operator in both defining the mechanism of tachycardia and identifying critical components amenable to ablation. There are several different approaches to mapping and ablating IFVT that may be used, which are summarized in Table 2, and discussed in further detail below. Traditional approaches, including pace and entrainment mapping, mapping the earliest ventricular electrogram during VT, and mapping the earliest fascicular electrogram during VT, have been well described but carry potential limitations. We also discuss the potential role of comparative mapping techniques.

Intraoperative Definition of Tachycardia Circuit
Several reviews of approaches to mapping and ablation have been published. We would encourage the reader to review these in detail as we seek to put them in broader context here. During mapping of the tachycardia circuit, 2 distinct potentials may be observed, typically termed the Purkinje potential (P2) and pre-Purkinje potential (P1) (Figure 3). The relative activation times vary in described studies between 5 to 25 and 30 to 70 ms pre-QRS, respectively. P2 reflects activation of the fascicle and Purkinje fiber near the fascicle and appears as a sharp, high-frequency potential. P1 reflects excitation at the entrance to the verapamil-sensitive zone in the septum. This potential is often lower in frequency than P2 and, when pacing at higher pacing rates, may be captured antidromically during tachycardia but captured orthodromically in sinus rhythm and thus may follow the ventricular complex. It is this association between fast conducting Purkinje fibers (P1) and slow conducting verapamil-sensitive fibers (P2) that characterize the substrate for reentry. Figure 4 demonstrates the putative reentry circuit and the electrograms to which P1 and P2 refer. Interestingly, although the above is true in left anterior and posterior fascicular VT, some have suggested that the upper septal fascicle works in the reverse direction, with Purkinje potentials activated in the reverse direction to that of common forms of IFVT (ie, P1 is activated retrogradely but P2 is activated antgradely).

The classic schema for mapping has been previously well described by Nogami et al. To achieve the best discrimination of P1 and P2 potentials and their participation in tachycardia, use of a multipolar electrode catheter to help define antegrade and retrograde activation patterns followed by attempts to entrain the fascicles to prove they are part of the circuit provides an excellent initial means of (1) defining the circuit and (2) determining whether the fascicle in question is involved in the circuit.

Critical Considerations When Mapping
First, performing rigorous maneuvers to define the arrhythmia mechanism is critical, such as pacing from a distant site to support whether the underlying mechanism is reentry or automaticity. If a diagnosis of reentry is supported, the operator must be careful to not solely rely on tagging sites of earliest myocardial activation. Because of the fact that there may be arborization of Purkinje fibers beyond the region of reentry, there may be several early myocardial sites with relatively late sites in between. Thus, the earliest site is characterized not only by the earliest myocardial signal but also by defining earliest P1 and P2 (ie, conduction signals). Furthermore, use of ICE and fluoroscopy to define close by endocavitary structures and to optimize catheter contact is critical, as the Purkinje signals may be small, easily missed, and occur on the surface of other structures. Given that critical elements of the circuit are normally superficial, careful catheter manipulation so as not to cause mechanical injury and thus render the VT noninducible is important.

Simultaneous use of a multiprobe catheter along with point-to-point mapping may further help when mapping IFVT. The goal when using both together is to be able to discriminate myocardial and conduction signals across a large region of myocardium with closely spaced electrodes to optimize signal discrimination. Using 1-mm electrodes with 1- to 2-mm spacing oriented along the path of the fascicle would optimize both signal discrimination and timing of relative activation. Thus, 2 points of access to the left ventricle, whether by 2 trans-septal punctures or a combined retrograde and trans-septal approach, may be needed to facilitate placement of both the multielectrode catheter and the ablation catheter.

One of the main limitations to the use of a multiprobe catheter is being able to line it up with the course of the fascicle. Typically in human hearts, the angle between the bundle...
### Table 2. Approaches to Mapping and Ablating Fascicular Ventricular Tachycardia

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<thead>
<tr>
<th>Approach</th>
<th>Utility for Fascicular VT</th>
<th>How to Do</th>
<th>Benefits</th>
<th>Pitfalls</th>
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</table>
| Map earliest ventricular electrogram during VT | Zero to low               | Map earliest myocardial signals during arrhythmia and identify/ablate the earliest area | Identifying a relatively fixed earliest ventricular electrogram can serve as a fiducial reference for other mapping | Earliest myocardial signal is not a critical part of the circuit  
Potential for multiple early areas of myocardial activation because of arborization of Purkinje system distal to VT circuit  
If one records signals that have mixed components (eg, ventricular and Purkinje signals), it may be difficult to impossible to interpret the return signal  
May be multiple distal means of exit and return because of the extensive arborization of the Purkinje system, thus making the timing of the return difficult to interpret |
| Entrainment mapping with fixed output at various sites | Zero to low               | Stimulate at a fixed cycle length at various sites to determine whether in circuit | May help define if arrhythmia mechanism reentrant or automatic when performed at varying distances from circuit | Needs to be a discrete area of stimulation because if one captures sites that are both in and out of the circuit, results of entrainment may be flawed  
If one records signals that have mixed components (eg, ventricular and Purkinje signals), it may be difficult to impossible to interpret the return signal  
May be multiple distal means of exit and return because of the extensive arborization of the Purkinje system, thus making the timing of the return difficult to interpret |
| Pace mapping at fixed output                  | Zero to low               | Deliver electric stimulation at multiple sites to identify regions with similar QRS morphology to clinical arrhythmia | Does not rely on arrhythmia sustainability | May or may not be capturing fascicle/Purkinje fibers during stimulation  
Will capture surrounding myocardium not involved in circuit leading to difference in QRS morphology  
Potential for variable QRS morphology during VT— inability to use a fixed QRS morphology against which to map |
| Target earliest fascicular signal             | Low to moderate           | Map earliest fascicular and Purkinje potentials during VT | Mapping critical components of circuit (ie, fascicles/Purkinje fibers) rather than secondarily activated region (ie, myocardium)  
May be effective for automatic arrhythmias | Most fascicular VT reentrant and thus earliest signal is relative  
If earliest signal identified above level of circuit because of low density of mapping, this may not eliminate circuit despite eliminating fascicular conduction proximally |
| Pace mapping at variable (ie, high, low, and very low output) combined with similar stim to QRS and concurrent abnormal fascicular/Purkinje signals | Low to moderate           | Identify fiducial reference on QRS complex (see caveats in text) and identify sites at which fascicle/Purkinje signal to QRS equal to stim to QRS during pacing at variable output | Does not rely on arrhythmia sustainability (although still must be inducible)  
More likely to differentially capture local myocardium versus local myocardial+fascicle  
Able to determine if activating elements that are proximal to the circuit based on different stim to QRS | Will capture surrounding myocardium not involved in circuit leading to difference in QRS morphology from VT  
Potential for variable earliest QRS during VT— inability to use a fixed portion of QRS (even earliest portion of QRS) against which to map  
Earliest QRS may vary both during pacing and during VT when capturing conduction fibers because of multiple secondary exits through distal Purkinje system  
Local fascicular or Purkinje signal may be normal in appearance even in patients with fascicular VT |
| Fascicular entrainment                         | High                      | Stimulate locally at sites where fascicular/Purkinje signals seen to capture local fascicle/Purkinje fiber (not just myocardium). Cycle length of pacing should be determined by fascicle—fascicle timing rather than QRS—QRS timing because of potential for multiple secondary exits/variable cycle length | Depend on a definite return electrogram (not ventricular but fascicular)  
More accurate reflection of circuit because ensuring fascicular and not myocardial entrainment | Arrhythmia must be sustainable to allow for entrainment  
Will need to use a multielectrode catheter to define fascicular activation sequence to differentiate concealed vs manifest (cannot depend on QRS morphology)  
Need to ensure capture of local fascicular signals  
If multiple means of secondary exit and return, there may be shifts in timing of the return beat  
Need to be able to differentiate local fascicular/Purkinje from myocardial signal |
of His and left bundle is around 15°, the angle between the left bundle and the takeoff of the left anterior fascicle is 50° to 75°, and the angle between the left bundle and the takeoff of the posterior fascicle is 15° to 30°. If one appreciates the natural angle between the His bundle and the left posterior or left anterior fascicle takeoff, positioning the multielectrode catheter to approximate the course of the desired fascicle may be made more straightforward.

Pace and Entrainment Mapping for IFVT

Pace Mapping
In many atrial and ventricular arrhythmias, pace mapping to try and reproduce the same activation pattern/QRS morphology may be used as a surrogate for the target site. The issue in the case of any Purkinje or fascicle-related arrhythmia, whether automatic or reentrant, is that it is almost impossible to capture the specialized conduction fibers without also capturing surrounding myocardium and perhaps other nearby Purkinje fibers with disparate exits. Thus, 1 of 2 events can happen—(1) a similar pace map is seen, but because of a large virtual electrode capturing critical circuit elements that are farther away, ablation locally would not necessarily be successful or (2) a significantly different pace map is seen despite being at the site of a critical circuit component because of simultaneous capture of local ventricular myocardium or differences in ventricular activation through distal components of the fascicular–Purkinje system during pacing versus tachycardia. Although several authors have suggested the ability to specifically capture Purkinje fibers during both pace and entrainment mapping, the potential limitations of this approach need to be understood. 47

Entrainment Mapping
The same issues noted for pace mapping apply to entrainment mapping. For entrainment mapping to succeed, there needs to be a discrete area of stimulation, and one should be able to record a dependable return electrogram with the assumption that return can only occur through a single retrograde limb of the reentry circuit. However, if one captures sites that are both in and out of the circuit, results of entrainment may be flawed. In addition, if one records signals that have mixed components (eg, ventricular and Purkinje signals), it may be difficult to impossible to interpret the return signal. Finally, there may be multiple distal means of exit and return because of the extensive arborization of the Purkinje system, thus making the timing of the return similarly difficult to interpret.

Consideration must also be given to atrial entrainment during IFVT. Entrainment by atrial pacing may suggest easy access of the conduction system to the circuit. This, in turn, supports a role for the fascicles. Thus, although ventricular entrainment may support a reentrant mechanism, atrial entrainment may suggest a critical role of the fascicles. 21

Defining the Earliest Ventricular Activation
One of the main limitations during mapping of IFVT is the potential for variable activation of the ventricle. It is well recognized that during activation of the His-Purkinje system, not all Purkinje–myocyte junctions are activated with every beat. Thus, there is the potential for variable QRS morphology and coupling intervals. One of 3 events can occur during IFVT as a result: (1) the QRS morphology and earliest ventricular activation can be fixed; (2) the QRS morphology may be slightly variable, but the earliest intracardiac activation is fixed with variable recruitment of surrounding Purkinje fibers causing a slightly variable morphology; or (3) the QRS morphology and earliest intracardiac electrogram may both vary significantly over time. Attempting to define each of these situations will help the operator in identifying a reasonable fiducial reference—whether the earliest surface QRS in case 1, a fixed intracardiac reference in case 2, or no reliable fiducial reference in case 3. It is important to note than when stating earliest ventricular activation, we are referring to the earliest local V during tachycardia and not the earliest V during sinus rhythm.

Defining the Earliest Fascicular Signal
Defining the earliest fascicular signal is necessary when mapping IFVT because they reflect critical components of the circuit rather than secondarily activated regions (ie, ventricular myocardium). However, fascicular signals may or may not be easily differentiated from the associated ventricular signals. For example, depending on the activation of the fascicle relative to the immediately surrounding myocardium, there may not be an apparent isoelectric period during tachycardia thus impeding appropriate signal discrimination. Furthermore, most IFVT is reentrant, and, thus, the concept of early is relative. Finally, if the earliest signal is mistakenly thought to be above the level of critical components of the circuit because of low-density mapping, the VT circuit may not be eliminated despite elimination of proximal fascicular conduction.

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Table 2. Continued

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<tbody>
<tr>
<td>Comparative mapping between sinus rhythm, high output pacing, and VT using a fiducial electrogram reference (ie, earliest V)</td>
<td>High</td>
<td>Look at timing of local fascicle/Purkinje signal compared with earliest V in sinus rhythm, during pacing, and during VT. If timing is same as during VT, then signals are in or distal to circuit. If not, then likely proximal to circuit</td>
<td>Depend on the earliest V (not QRS) against which to compare Does not depend on arrhythmia sustainability (though should be inducible) May be used to define circuit length from most proximal portion onward</td>
<td>Portions distal to the circuit will exhibit similar timing to earliest V (Figure 5D) and thus matching retrograde sequence of activation with pacing versus tachycardia should be evaluated Depends on having a dependable fiducial ventricular reference Need to be able to differentiate local fascicular/Purkinje from myocardial signal</td>
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VT indicates ventricular tachycardia.
Additional Approaches Requiring Validation

Comparative Mapping
Although the previously mentioned approaches (defining P1 and P2, using pace and entrainment mapping, identifying the earliest diastolic and presystolic signals) have been widely reported, fewer authors have discussed the role of comparative mapping techniques. The principles of comparative mapping to define the tachycardia circuit are natural extensions of those previously reported by Nogami et al but may offer a systematic approach to defining critical circuit components to IFVT. The main limitation, however, is the need for dependable comparative analysis of individual signals during sinus rhythm versus tachycardia. The purpose of this section is to highlight principles that may be useful for assessment of fascicular VT but require further study to determine (1) their efficacy relative to other approaches and (2) the percentage of patients in whom they can be realistically used. Specifically, whether such rigorous evaluation affords incremental value above other techniques is unclear and requires further study. Although these methods still require systematic validation, the concepts are critical to consider and relevant to all arrhythmias.

Comparative Timing Against Sinus Rhythm
One method of defining whether the mapping site is in the circuit may be using comparative timing of the local signals against sinus rhythm. If a catheter is placed at a site along the fascicle and the P2 signal is recorded, one can measure the
timing from the local signal to the earliest ventricular electrogram during tachycardia. If this timing during sinus rhythm is the same as during tachycardia, then that spot is likely either the target site or distal to it because one would assume that regardless of whether one was in tachycardia or in sinus, the time to get from that local signal to the ventricular myocardium should be about the same. The timing of more proximal elements (eg, the His bundle) compared with ventricular activation, however, will be shorter during tachycardia than that during sinus rhythm (Figure 5A).

Thus, one could identify a site where the fascicle-to-ventricular electrogram timing is the same during both tachycardia and sinus rhythm and sequentially map back to the more proximal elements of the fascicle/bundle until the timing starts to become earlier during tachycardia. The point at which the timing goes from being equal in both rhythms to different may indicate the most proximal elements of the circuit.

However, this method does have its limitations. First, a point ablation is unlikely to be effective, and one might have to cross through the fascicle at or below this spot somewhere along the circuit. In addition, if during sinus rhythm there is a secondary exit that is getting to the local ventricular electrogram faster than that during tachycardia, one may never get an exact timing match. One way to avoid this issue of secondary exits is to keep a separate fiducial reference for earliest ventricular activation against which to compare. This would be the ideal method for mapping. The limitation, of course, is creating a stable reference, in which case a screw in electrode may be considered.

Comparative Mapping During Pacing
One method of mapping that may be complementary to comparing signal timing during sinus is to use a surrogate of para-Hisian pacing—high versus low output pacing in the region of the fascicle or Purkinje tissue. The use of this is most relevant for certain more microreentrant causes of IFVT. In the fascicular region, high output pacing would be expected to capture both the insulated fascicle and the local ventricular myocardium, but one would expect a paced QRS morphology different from that of tachycardia. If the stimulus to the earliest ventricular signal is similar during high output pacing and during tachycardia, then this suggests that the fascicle is part of the circuit, as long as the QRS morphology during pacing is different. However, if one paces proximal to critical portions

![Figure 4. An example of the reentry circuit thought to occur during fascicular ventricular tachycardia (VT). P1 reflects the low-frequency signal during tachycardia that is earlier pre-QRS (bottom left) and occurs right after the turn around close to the proximal left bundle and bundle of His. P2 reflects the sharper signal closer to the start of the QRS. Following P2 comes the ventricular signal (V) in association with generation of the QRS complex.](image-url)
Figure 5. A, A simplified schematic of mapping during sinus rhythm and tachycardia during left posterior fascicular ventricular tachycardia (VT). This is meant to highlight comparative mapping principles given that the circuit in the Purkinje network is not necessarily linear and there is extensive potential for bystander conduction during VT. Numbered sites are mapping sites where the catheter is placed. V indicates the earliest ventricular signal during tachycardia being used as a fiducial reference. Proximal to the circuit site, the timing from the fascicular signal (f) to V will be longer in sinus than in tachycardia. In the circuit, it will be equal. However, given the potential for multiple secondary exits, a catheter placed within the distal Purkinje system (3) may exhibit the same timing to the earliest V during sinus and tachycardia, but ablation here would not necessarily terminate tachycardia given it acts as a secondary exit site. Note fascicular and Purkinje fibers are in red for purposes of discriminating between the two. P refers to local Purkinje signal seen during point-to-point mapping, not specifically P1 vs P2. Note that the schematic diagram is meant to point out timing and that both fascicular and ventricular electrogram morphologies will necessarily be different during tachycardia and sinus. B, Actual tracings from a patient with fascicular VT. The first pair of ablation electrograms (1) show a site proximal to the VT circuit during mapping, where the fascicle (f) to ventricular electrogram time was longer during sinus than tachycardia. Below that was the electrogram at the first spot where there is a Purkinje/fascicle (P) timing to the local V equal in sinus and tachycardia. Ablation here resulted in termination of the arrhythmia. (Continued)
Figure 5 Continued. C, Effects of high, low, and very low output pacing on signal characterization. The examples are most relevant to focal and microreentrant versions of idiopathic fascicular ventricular tachycardia (IFVT), with schema 2 not necessarily being relevant for cases of macroreentrant IFVT. The pacing sites are blue and the overlying earliest ventricular electrogram is overlaid in purple. With high output pacing on the fascicle, one will capture both the insulated fascicular fiber and local ventricular myocardium. Proximal to the circuit, fascicular signal to the earliest V will always be greater than during tachycardia. If, however, one is in the circuit, with high output pacing, the stim to earliest V will be equal to fascicle to V during tachycardia, but when the fascicle is not captured, stim to V will then be longer (although fascicle to V will remain similar). In case (3) where one is pacing at the earliest Purkinje exit, high and low output pacing may capture both Purkinje and local ventricular myocardium, resulting in a different QRS morphology than tachycardia. However, if very low output pacing only captured the distal Purkinje fiber, this may result in the same QRS morphology as tachycardia (please note even at very low outputs, it may be impossible to only capture the Purkinje fiber and not the surrounding ventricular myocardium). Because this site is in the circuit, pV and SV should be the same for all pacing situations. However, if one paces at a distal, secondary exit site (case 4), one might expect that the stim to earliest V during pacing might actually be greater than during tachycardia given that now the stimulus to earliest V must get back to the site either via retrograde conduction through the Purkinje system or via ventricular myocardium. However, given the rapid nature of Purkinje conduction, it is possible that the difference will be minimal/not measurable. The paced QRS morphology during very low output pacing in case (4), if only the Purkinje fiber was captured, will likely exhibit subtle differences given the exit site is different than that during tachycardia. IV, fascicle to earliest ventricular electrogram timing; PV, Purkinje to earliest ventricular electrogram timing; SV, stimulus to earliest recorded ventricular electrogram timing. Subscripts refer to intervals as noted during high output (high), low output (low), and very low output (very) pacing done during sinus and during tachycardia (tach). D, Pacing to look at retrograde activation sequence when pacing at 2 different sites where local fascicular/Purkinje potential timing to the local earliest recorded ventricular electrogram (V) was the same in both sinus and during tachycardia. In the case of (4), we are in the circuit, and the retrograde activation sequence is the same as the P2 activation sequence during tachycardia. However, when pacing at site (2), the activation sequence is different despite a similar local signal to earliest ventricular electrogram (V) timing. Note that the fascicular/Purkinje signals are highlighted in red. The numbers 1 to 6 indicate individual bipoles along a multipolar catheter (green) placed along the left posterior fascicle. Also, note that the earliest recorded ventricular electrogram (V) may or may not have a Purkinje potential identified.
of the circuit, the timing will be shorter during tachycardia. In turn, if the pace map is identical to that of tachycardia with high output and low output pacing, one has to suspect that either the tachycardia is, in fact, not IFVT and traditional myocardial approaches to mapping may be needed or one is at the myocardial exit site (Figure 5C).

One caveat to this approach is when pacing directly on the Purkinje fibers, which are not insulated. There, very low output may capture Purkinje fibers alone without capturing the surrounding myocardium. If the paced morphology is identical to that of tachycardia during very low output pacing, but at higher outputs the morphology is different, and the stimulus to QRS is very short similar to that seen during tachycardia, then one knows the particular Purkinje fiber is of value to the circuit (Figure 5C).

Of note, this schematic idea requires validation but adopts many of the principles of high and low output pacing used in other areas of VT mapping. One key factor to consider is that all the schemas described in Figure 5C are likely to work during focal or macroreentrant causes of VT. However, as with any macroreentrant VT, schema number 2 in Figure 5C may not be effective, in part because of the fact that antidromic capture/activation also needs to be considered.

**Pacemapping of Retrograde Activation to Identify Critical Circuit Elements**

In addition to comparative mapping of the antegrade activation characteristics noted above, comparing retrograde activation is similarly critical. Although antegrade activation during pace mapping may be of little value because of simultaneous capture of ventricular myocardium, retrograde conduction does not care whether or not the ventricular myocardium is captured. One would expect, when pacing at the target site, the timing of the pacing stimulus to the retrograde His should be similar during pacing as would be the local fascicular signal to the retrograde His during tachycardia. In isolation, this approach is of limited value, but when used in combination with comparative mapping approaches noted above, it may help further confirm the target site.

Evaluation of this retrograde sequence during pacing serves as an adjunct. Using comparative mapping, similarity in timing between local fascicular or Purkinje and earliest local ventricular electrogram timing implies one is at a point within or distal to the proximal end of the circuit. However, it is still possible that there may be multiple exits and that the catheter is at a secondary exit site. However, if one also compares retrograde activation during pacing at this site, if the retrograde activation sequence is different during pacing than tachycardia, this implies the site was a secondary exit but not a critical portion of the circuit. The finding of retrograde Purkinje/fascicular activation sequence being similar during tachycardia and pacing along with similar fascicular/Purkinje to ventricular timing during both sinus rhythm and tachycardia implies that this is at a critical portion of the circuit (Figure 5D). If the latter is seen but not the former, mapping may be done more proximally along the fascicle course until this finding occurs. This approach is essentially the same as pace mapping for other arrhythmias, except instead of comparing the surface QRS during pacing versus during tachycardia, instead here we use the intracardiac electrograms given the aforementioned potential for a high degree of variability in surface QRS morphology during fascicular VT.

**Approach to Ablation of IFVT**

Once the mechanism and the responsible fascicle is defined, it is critical to consider how one approaches ablation. One option given aforementioned limitations of traditional mapping techniques and particularly if there is high suspicion of IFVT but it proves noninducible or nonsustained is to go upstream of the presumed critical site and simply ablate through the proximal aspect of the fascicle, thus preventing conduction through all distal elements. However, there are 3 issues related to this: (1) this may require more ablation than otherwise necessary; (2) if there is interlinking between components of the more distal fascicle and Purkinje fibers, there may still exist potential for reentry despite elimination of the conduction through more proximal elements; and (3) proarrhythmia may occur because of excessive ablation. Thus, having a systematic approach to mapping, defining the electrograms and the circuit and deciding where to ablate is critical.

Another commonly used ablative approach is to identify the earliest presystolic or diastolic fascicular or Purkinje signal relative to the QRS during tachycardia and ablate there, which will likely work in >50% of cases. Alternatively, one could map the earliest ventricular electrogram and, near that, ablate a fascicular or Purkinje signal. The limitations of these approaches are several, including the fact that for reentry a point ablation for a wide isthmus may not be effective and, if ablating upstream of the circuit, there may be other connections to the muscle or within the fascicular–Purkinje network. In addition, discriminating these signals can be difficult. Although fascicular signals may be well separated from local ventricular activation because of the presence of a fibrous coat insulating the fibers (resulting in a reasonable isoelectric period), there may not be a similar isoelectric period separating Purkinje and ventricular activation. Furthermore, particularly when mapping during sinus rhythm, if there is slow conduction through a fascicle or Purkinje fiber such that local ventricular activation occurs before those fibers can reach their target, then there may be significant obfuscation of the signal. However, one method of better differentiating myocardial from fascicular/Purkinje signals would be to interpolate premature ventricular contractions during tachycardia to separate the signals, although this would have to be repeated at every mapped point. This will afford 2 benefits: (1) we can define whether the mechanism is reentrant or automatic based on resetting characteristics and (2) based on which signals were moved and whether the tachycardia reset or not we can determine whether the perceived signals are critical to the arrhythmia and may be reasonable ablation targets.

Ideally, if one can map during tachycardia using any or all of the techniques previously mentioned and compare signals against those seen during sinus rhythm to identify the portions of the fascicles most critical to arrhythmia propagation, then ablation can be targeted at these most critical sites while salvaging areas that may not be as relevant. However, these
approaches need to be balanced against the limitations, which include the need to repeatedly induce tachycardia and having a well-placed multipolar catheter.

Several final key points need to be considered during ablation. First, given that the fascicular and Purkinje fibers are relatively superficial, transmural lesions are typically not necessary to achieve success. In addition, during ablation, there is potential to cause activation of the Purkinje tissue and to induce ventricular fibrillation. Finally, premature ablation without fully defining the circuit elements first should not be done as ablation prematurely proximally or distally may make further analysis/acquisition of signals difficult (eg, ablation of a secondary exit during more distal ablation leading to a change in QRS morphology but with continued tachycardia).

Ablation Outcomes
Overall success rates for ablation of IFVT range from 70% to 90% over long-term follow-up.52,53 Over a follow-up of almost 5 years, in those who recurred, a shorter VT cycle length at baseline was the only predictor of recurrence, and most commonly recurrence involved the same fascicle, although in a third involved the left upper septal fascicle. The upper septal fascicle in IFVT has been suggested to be an orthodromic form of IFVT and =50% of patients presenting with this form of IFVT will have had a previous ablation for a more common form related to the left anterior or posterior fascicles.44 The role of creating fascicular or partial fascicular block in patients with IFVT is unclear, although it has been suggested that in patients with noninducible tachycardia, creation of at least partial fascicular block may serve as a reasonable end point.54 However, others have suggested that in cases in which mapping during tachycardia can be performed, the development of fascicular block may be unnecessary.55

Conclusions
IFVT is a common source of arrhythmia. Fascicular ventricular arrhythmias may occur in both structurally normal and abnormal hearts. However, the traditional paradigm of IFVT consists of verapamil-sensitive tachycardias that occur in the setting of an otherwise structurally normal heart. Although pharmacological therapy may be effective, ablation, especially when VT is inducible at the time of electrophysiology study, has a high success rate. Differentiation of VT due to the fascicular system versus surrounding structures (eg, the mitral annulus or papillary muscle) can be difficult but possible with careful mapping and characterization of the mechanism of arrhythmia. Although ablation undertaken during sinus rhythm may be effective, ideally ablation should be done in VT to optimize likelihood of success but requires careful mapping of fascicular, Purkinje, and myocardial potentials. Future therapies may allow for improved targeting of the critical circuits of IFVT while avoiding damage to adjacent myocardium, but use of such therapies and whether they may improve outcomes of ablation remains to be seen.

Acknowledgments
We would like to acknowledge the contributions of Dr Siva Mulpuru in providing relevant case slides and figures.

Sources of Funding
S. Kapa is supported by a Mayo Clinic Department of Medicine Career Development Grant.

Disclosures
None.

References
Fascicular Ventricular Tachycardia Management


Fascicular Ventricular Arrhythmias: Pathophysiologic Mechanisms, Anatomical Constructs, and Advances in Approaches to Management
Suraj Kapa, Prakriti Gaba, Christopher V. DeSimone and Samuel J. Asirvatham

Circ Arrhythm Electrophysiol. 2017;10:
doi: 10.1161/CIRCEP.116.002476
Circulation: Arrhythmia and Electrophysiology is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 1941-3149. Online ISSN: 1941-3084

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SUPPLEMENTAL MATERIAL

VIDEO LEGENDS

Video 1

Shown is the intracardiac echocardiography video of the ablation catheter on the false tendon as noted in Figure 2.