Maintenance of sinus rhythm by catheter-based ablation of atrial fibrillation (AF) has become a common strategy for symptom control. The cornerstone of AF ablation is pulmonary vein isolation (PVI) with both entrance and exit block. Wide area circumferential ablation (WACA) in the antrum has increasingly replaced pulmonary vein (PV) ostial ablation because of a higher success rate and reduced risk of PV stenosis. However, a percentage of patients require a second procedure for AF control. At repeat ablation, PV reconnection is a common finding, and occasionally, it is difficult to achieve true entrance and exit block, especially for the right pulmonary veins (RPVs).

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When faced with difficulty in obtaining RPV isolation, we follow a stepwise approach (Figure 1) to successfully identify the area of persistent connection. If WACA fails to achieve RPV entrance and exit block, some alternatives include (1) ablation more ostially and into the carina region, which potentially risks PV stenosis; (2) wider encirclement, which requires a larger ablation region and more radiofrequency application, and may be unsuccessful as a result of anatomic factors (in many cases because of the presence of the phrenic nerve in the septal aspect of the RPVs); or (3) mapping the activation pattern of the persistent connection. Voltage mapping can demonstrate the extent of prior ablation lesions and can also document lesion maturity at the interface of healthy tissue and scar. Activation mapping during pacing from the reconnected PV can reveal the connection pathways, which could be either via the left atrium (gaps in the line of WACA ablation) or connection to adjacent structures (RPV to right atrium). During pacing, if the earliest signal is on the left atrial side of the WACA line, there is a gap in the line, which should be remapped and the area of connection should be reablated. If, however, there is earliest activation in the right atrium (RA), there may be a direct connection between the RPV and RA.

Our hypothesis is that early RA activation may be the result of interatrial connections remote from the coronary sinus (CS), Bachmann’s bundle, or fossa ovalis. Although such connections exist on gross pathological specimens (Figure 2), to date, there are no reports of the electrophysiological characterization of the intercaval bundle during PVI procedures. Figure 1 in the Data Supplement). We report here a series of 4 patients with AF, in whom the appropriate diagnosis of an electrically conducting intercaval bundle was integral to the treatment of AF (see schematic outlines in Figure 1). Cases fulfilled the following criteria: AF ablation procedure in which entrance and exit block of the right-sided PV was difficult to achieve; earliest activation during RPV pacing was in the right atrium and not on the left atrial side of the WACA line; other connections between the left atrium (LA) and RA were not involved in PV reconnection; ablation in the RA resulted in durable PVI.

Case 1

A 69-year-old woman with coronary artery disease, hypertension, and symptomatic paroxysmal AF was referred to our institution for AF ablation after failing sotalol therapy. A WACA procedure was performed with transient isolation of the right superior pulmonary vein (RSPV). A 3.5 mm D-F EZ Steer Thermocool® Ablation Catheter ( Biosense Webster, Diamond Bar, CA) was used for ablation, which was limited to 30 W power, 42°C temperature, and 30 seconds (20–30 W on the posterior wall, 15–20 seconds) targeting 10 ohm impedance drops. There was acute reconnection of the RSPV. Activation mapping using EnSite™ NavX™ (St. Jude Medical, St Paul, MN) during RSPV pacing revealed earliest activation in the posterior RA near the superior vena cava (SVC). Ablation at the earliest site in the SVC–RA junction was required for durable entrance and exit block of the RSPV (Figure 3). There were no inducible atrial arrhythmias with burst atrial pacing at baseline or with isoproterenol infusion.

Case 2

A 57-year-old gentleman with paroxysmal AF presented with recurrent arrhythmias 18 months after initial PVI. The repeat procedure was notable for chronic reconnection of the RSPV, with difficulty achieving entrance and exit block, and atrial premature depolarizations from the RSPV triggered AF with isoproterenol infusion. Ablation was performed using a Thermocool® SF Nav Bidirectional D-F Curve ablation catheter ( Biosense Webster), with lesions limited to 20 to 40 W power for 15 to 30 seconds, targeting 8 to 10 ohm impedance drops. Pacing from the RSPV
revealed earliest activation in the RA before CS activation, and pacing from the RA revealed earliest activation in the RSPV before LA or CS activation (Figure II in the Data Supplement). During repeat isoproterenol infusion, RSPV atrial premature depolarizations triggered AF, and earliest activation was seen in the SVC. It was unclear if the trigger originated in the SVC or RSPV. The SVC was targeted for isolation, but circular ablation was limited by proximity to the phrenic nerve. Finally, ablation at the site of earliest RA activation during RSPV pacing achieved durable RSPV isolation without isolation of the SVC (Figure 4) and elimination of the AF trigger.

**Case 3**

A 53-year-old gentleman with diabetes mellitus, hypertension, and nonischemic cardiomyopathy presented with atypical atrial flutter 6 months after AF ablation. The index procedure consisted of PVI, LA roof line, anterior mitral annulus line, and cavo-tricuspid isthmus line. At the time of the second procedure, detailed electroanatomic mapping revealed chronic reconnection of the right inferior pulmonary vein (RIPV) reconnection, but burst pacing induced macro reentrant atrial flutter involving both atria. Both flutters were terminated by WACA around the right pulmonary veins (RPVs), but this did not achieve RPV isolation. Pacing maneuvers demonstrated activation patterns similar to previous cases and ablation at the RA septum achieved durable PVI. AAD indicates antiarrhythmic drug; MA, mitral annulus; and PAF, paroxysmal atrial fibrillation.
Prior ablation lines across the left atrial roof and from the RSPV to the mitral annulus demonstrated bidirectional block. Burst pacing from the coronary sinus to assess for inducible flutter resulted in atypical atrial flutter with proximal to distal CS activation (Figure V in the Data Supplement). Entrainment maneuvers from the proximal and distal CS excluded mitral annular flutter (Figure VII in the Data Supplement). Additionally, entrainment from the RIPV showed concealed fusion of both the P wave and the intracardiac electrogram as well as a post-pacing interval of <30 ms. Pacing from the RIPV had a long stimulus to surface P wave (presumably an entrance site), and entrainment from the posterior RA had a short stimulus to surface P wave (presumably an exit site; Figure 5). The difference in stimulus to P wave timings demonstrates a lack of direct RA capture with RIPV pacing.

Of note, the pacemap of the P wave was a 12/12 match to the flutter P wave. Ablation, using the same settings as Case No. 2, around the RIPV terminated the atrial flutter; however, there was neither entrance nor exit block demonstrated (Figure VI in the Data Supplement).

Figure 2. Gross anatomy of the intercaval bundle between right superior pulmonary vein (RSPV) and right atrium (RA). Exhaustive comparative anatomic review of >27 species of vertebrate hearts yielded multiple possible anatomic formations. In the human heart, muscle bundles perpendicular to the interatrial septum can cross from the posterior right atrium to the os of the right-sided pulmonary veins; insertion into the posterior RA between the superior vena cava (SVC) and inferior vena cava (IVC) defines the intercaval bundle. LA indicates left atrium. Adapted from Keith A, Flack M. The form and nature of the muscular connections between the primary divisions of the vertebrate heart. J Anat Physiol. 1907 Apr; 41(Pt 3):172–189. Reprinted with permission of the Anatomic Society of Great Britain and Ireland and with permission of John Wiley & Sons, Inc.

Figure 3. Ablation at the superior vena cava right atrium (SVC-RA) junction is required for isolation of the right superior pulmonary vein (RSPV). After wide area circumferential antral ablation (WACA), the right-sided pulmonary veins remained connected without exit block. Pacing the RSPV showed earliest activation in the right atrium at the SVC-RA junction. Ablation at the SVC-RA junction from the right atrium resulted in durable entrance and exit block from the right pulmonary veins (RPVs). Mapping was performed using EnSite™ NavX™ (St. Jude Medical, St Paul, MN).

Figure 4. Final ablation lesion set. Ablation lesions were delivered around the right pulmonary veins (RPVs) and also at the SVC-RA junction. Red dots represent full power lesions (30–40 W, >8 ohm impedance drops, 30 s), pink dots represent low power lesions (20 W, 15 s) on the posterior wall, and black dots represent sites of diaphragmatic capture with high output (50 mA) pacing. White dots are the ablation lesions in the right atrium (RA) that achieved pulmonary vein isolation (PVI). Anatomic maps were created using CARTO® 3D, and ablation was performed using a Thermocool® Catheter (Biosense Webster, Diamond Bar, CA).
After flutter termination, there was difficulty obtaining RIPV isolation. Further mapping revealed proximity to the phrenic nerve anteriorly, limiting potential ablation lesions to deeper in the PV, where there would be a risk of stenosis. The RIPV was paced and an activation map created to determine the exit site. Sites within the left atrium were late (left atrial appendage; distal coronary sinus; inferior/anterior left atrium). Earliest activation was found in the posterior right atrium (Figure 6). Finally, ablation in the RA at the site of earliest activation during RIPV pacing resulted in durable exit block (Figure VIII in the Data Supplement); entrance block was also subsequently confirmed. There was no reconnection with adenosine administration. Atrial burst pacing on isoproterenol did not induce any atrial arrhythmias.

**Case 4**

A 52-year-old man with nonischemic cardiomyopathy and obstructive sleep apnea presented with recurrent arrhythmias 3 months after prior AF ablation. At the time of repeat procedure, there was chronic reconnection of the RPVs (Figure IX in the Data Supplement). There was an area of healthier voltage around the anterior superior RPVs, indicating a gap in the prior ablation line. Atrial burst pacing on isoproterenol induced atrial flutter with proximal to distal CS activation (Figure X in the Data Supplement). Entrainment maneuvers revealed areas of the left atrium to be late, but areas of the right atrium and...
RIPV to be close to the circuit (Figure 7). Again, the long stimulus to P wave from the RIPV and the short stimulus to P wave from the RA indicated entrance and exit sites of the circuit, respectively (Figure XI in the Data Supplement). Ablation, as described in Case No. 2, around the RPVs resulted in tachycardia termination without entrance and exit block. Pacing from the RIPV resulted in earliest activation in the RA and latest activation at the posterior border of the LA WACA line, and RA septal pacing resulted in earliest activation in the RPVs (Figure 8). Remarkably, propagation maps during the atrial flutter and during RIPV pacing are closely matched, with earliest activation in the RA (Videos I and II in the Data Supplement). Finally, ablation at the site of earliest activation (in the RA) resulted in durable entrance and exit block from the RPVs (Figure XII in the Data Supplement). There was no acute reconnection with adenosine administration. Atrial burst pacing at baseline and on isoproterenol did not induce any atrial arrhythmias.

Discussion

We present a series of cases in which PVI (entrance and exit block) required ablation in the RA remote from commonly established interatrial connections (Bachmann’s bundle, fossa ovalis, and coronary sinus). We posit here that a mechanism for such a finding involves electric conduction via intercaval bundle fibers connecting the RPVs to the RA. In 1907, Dr Keith and Mr Flack, who had previously described the existence of atrio-ventricular nodal conducting tissue, undertook a comprehensive anatomic review of vertebrates to more closely examine the connections between the right and left atria. After carefully dissecting and cataloguing over 27 species of vertebrates (including over 30 human specimens), the researchers concluded that there exist many muscle bundles that connect the right and left atrium: “It may be, however, that there are also remnants of the sinus in the left auricle of the human heart….It is possible, therefore, that, as part of the auricular canal…expands, a part of this sinus musculature is also involved in the process, and may persist in the left auricle of the human heart around the orifices of the pulmonary veins” (see Figure I in the Data Supplement). Since that original supposition, others have confirmed the existence of these intercaval bundles. Although others have described such muscle bundles on gross pathology, we present here the first detailed electro-anatomic description.

Our patients had previously undergone AF ablation procedures with wide area circumferential antral ablation for...
PVI. An intriguing possibility is that WACA allows for large bundles of muscle remain intact within the pulmonary veins; some of these muscle bundles traverse epicardially and can span from the RPVs to the RA. One criticism of this concept is that the first procedures demonstrated entrance and exit block, despite the presence of an intercaval bundle. There could be several explanations for this. First, lesions near the intercaval bundle could have caused edema and pressure, transiently blocking conduction; resolution of edema over days likely resulted in reconnection of the PV. Second, the original procedures were likely proximal enough or antral enough to achieve isolation by ablating near the LA insertion of the intercaval bundle. Indeed, given the fiber orientations of intercaval bundles, this hypothesis also provides a reasonable physiological mechanism for durable isolation to sometimes require carinal ablation of the RPVs (see Figure I in the Data Supplement). Additionally, it is possible that PV isolation was incorrectly documented after initial PVI lesions were performed, and true isolation had not been achieved until RA ablation was performed. On review of these cases, however, this explanation seems unlikely. Finally, a last unlikely explanation could be neurological: initial WACA lesions injure critical neuronal plexi that could regenerate and preferentially conduct via alternate pathways, such as the intercaval bundle. Although not seen in humans, this has been reported in the possum and zebrafish. Of note, standard 30 day transtelephonic monitors worn 3 months after the ablation procedures revealed no recurrence of atrial arrhythmias in all 4 patients.

These normally quiescent fibers can manifest their conduction properties when atrial premature depolarizations from the RPV trigger AF or are essential components of macroreentrant circuits. Rather than ablation inside the pulmonary vein (risking PV stenosis) or anteriorly (risking phrenic nerve injury), mapping and ablation in the right atrium may be indicated in those patients for whom RPV isolation is difficult. A more systematic study of RA ablation required for RPV isolation could be helpful to elucidate this phenomenon.

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Disclosures

None.

References


KEY WORDS: atrial fibrillation • atrial flutter • catheter ablation
Electroanatomic Mapping of the Intercaval Bundle in Atrial Fibrillation
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SUPPLEMENTAL MATERIAL

Figure Legend

Supplemental Figure 1. (A) RSPV pacing activation sequence. After WACA, anterior mitral line, LA roof line, and attempted isolation of the RPVs, there is no exit block. Pacing the RSPV with the lasso shows earliest activation in the ablator (in the RIPV), then in the Crista, then proximal to distal coronary sinus. (B) Crista pacing activation sequence. Pacing Crista 4 with the ablator at the LA roof demonstrates activation from the RSPV first, then LA roof, then CS from proximal to distal. Taken together, these figures are consistent with a connection between the two atria separate from Bachmann’s bundle, fossa ovalis, or CS.

Supplemental Figure 2. Chronic reconnection of the right inferior pulmonary vein. The ablator is in the RIPV and has a sharp EGM with baseline RA appendage pacing. The lasso in the LSPV shows an isolated PV potential and there is a farfield LA appendage signal.

Supplemental Figure 3. Voltage mapping indicates areas of prior ablation. A high density electroanatomic map demonstrates ablated signals surrounding the LPVs and the RSPV, but normal voltage at the posterior RIPV. Also seen are the LA roof line and anterior mitral line (RSPV to MA). Electroanatomic maps were created using CARTO 3D. The color scale represents 0.2 mV (red) to 0.5 mV (purple).

Supplemental Figure 4. Induced atrial flutter. Burst pacing during isoproterenol infusion resulted in atrial flutter with cycle length of 369 ms and with proximal to distal activation in the CS. The lasso is in the RIPV and the ablator is at the RIPV os.
Supplemental Figure 5. Ablation in RIPV terminates flutter without isolating the vein. With the ablator at the RIPV os and the lasso in the RIPV, there is transient dissociation of the RA from the RIPV during termination of the atrial flutter.

Supplemental Figure 6. (A) Entrainment response from distal CS. A long PPI-TCL demonstrates the distal CS to be out of the circuit during atrial flutter. (B) Entrainment response from inferior/anterior LA. A long PPI-TCL demonstrates the LA, at the site of the anterior mitral line, to be out of the circuit during atrial flutter.

Supplemental Figure 7. (A) Ablation in RA leads to RIPV exit block. The blue dot shows the site of transient RIPV exit block during ablation. (B) Permanent RIPV exit block after multiple RA lesions. Red dots represent all the delivered ablation lesions.

Supplemental Figure 8. (A) Chronic reconnection of the RPVs. The ablator remains in the RSPV, and the lasso is moved from the RSPV to the RIPV. There is chronic reconnection of both veins with lack of entrance block during normal sinus rhythm. (B) Voltage map. The relatively normal voltage at the RPVs demonstrates a lack of durable ablation lesions.

Supplemental Figure 9. Induced atrial flutter. Burst pacing from the CS during isoproterenol infusion results in atrial flutter with cycle length of 301 ms and proximal to distal activation in the CS. The ablator is in the LA and the lasso is in the RSPV.

Supplemental Figure 10. P wave morphology during tachycardia and during entrainment. The longer stimulus to P wave from the RIPV and the shorter stimulus to P wave from the RA indicate probably entrance and exit sites of the flutter circuit, respectively. There is similar P wave morphology (concealed fusion) with some artifact from the high output pacing channel.
Supplemental Figure 11. Ablation in the RA results in RPV isolation. White dots represent the prior WACA lesion set; black dots represent sites of phrenic capture. Purple dots represent ablation in the RA, which resulted in isolation of the RPV with entrance and exit block.

Supplemental Video 1. Propagation map of tachycardia. During atrial flutter, activation begins in the RPVs, spreads to the RA from posteromedial to anterolateral, and then comes back to the CS and LA.

Supplemental Video 2. Propagation map of RIPV pacing. During RIPV pacing, the activation pattern is similar to the tachycardia.
Supplemental Figure 1. Pacing activation sequence.
Supplemental Figure 2. Chronic reconnection of the right inferior pulmonary vein.

Lasso in LSPV and Abl in RIPV
Supplemental Figure 3. Voltage mapping indicates areas of prior ablation.

Voltage Map

Multiple electrode
High density map (1741 points edited)

1a
1b

1- Wide circumferential PVI
   a. LPVs isolated
   b. RIPV reconnected
   - Posterior voltage (esophagus)

2- Roof line
3- RSPV to MA line
Supplemental Figure 4. Induced atrial flutter.
Supplemental Figure 5. Ablation in RIPV terminates flutter without isolating the vein.
Supplemental Figure 6. Remote entrainment responses.
Supplemental Figure 7. RA ablation.

A

Ablation in RA leads to PV exit block

B

Ablation in RA until permanent PV exit block
Supplemental Figure 8. Chronic RPV reconnection and voltage map.
Supplemental Figure 9. Induced atrial flutter.
Supplemental Figure 10. P wave morphology and entrainment.
Supplemental Figure 11. Ablation in the RA results in RPV isolation.