diopathic ventricular arrhythmias (VAs) arising from the left ventricle (LV) are often accessible for catheter ablation from the aortic sinuses of Valsalva or adjacent to the mitral annulus (MA). The aortic and mitral valves are direct apposition and attach to an elliptical opening at the base of the LV known as the LV ostium. The VAs arising from this region are being increasingly recognized as targets for catheter ablation. This review describes the anatomic features of the LV ostium and the electrocardiographic, electrophysiological, and angiographic characteristics that are relevant to the mapping and ablation of these arrhythmias.

Anatomy of the LV Ostium

The dominant central structure of the heart is the junction of the aorta with the LV. Fundamental for understanding idiopathic VAs arising near the aortic and mitral valves are 2 concepts: first, these arrhythmias arise from the LV ostium (Figure 1); and second, the LV ostium is covered by the aorto-ventricular membrane, a tough fibrous structure which is perforated by the aorta anteriorly and the mitral valve (MV) posteriorly (Figure 2). The anatomic concept of the LV ostium and its covering, the aorto-ventricular membrane, are based on the pioneering work of McAlpine.

The Anterior Division of the Aorto-Ventricular Membrane Within the LV Ostium

The aorta is joined to the LV ostium at an angle of ≈30% above the horizontal plane with the noncoronary cusp (NCC) most inferiorly and the left coronary cusp (LCC) most superiorly (Figures 1 and 3A). Rather than a circular fibrous aortal annulus, in reality the anatomy is much more complex with 3 membranous attachments at the base of the right, left, and noncoronary cusps (Figure 2). These attachments consist of less than one half of the circumference of each aortic sinus cusp (ASC). The most anterior attachment of the aorta to the LV ostium is the right coronary cusp (RCC) (Figure 3B), which is in contact with the LV ostial myocardium over a distance of 16.5±3 mm (Figure 4A). When viewed from the superior aspect of the RCC, LV muscle can be seen at the base of the cusp. The RCC has an average depth of 23.2±2.7 mm with the ostium of the right coronary artery (RCA) located ≈15 mm from the nadir of the cusp (Figure 3C).

The LCC forms the lateral and postero-lateral attachment of the aorta to the LV ostium (Figure 2). The LCC is in contact with the LV ostium in the antero-lateral portion of the cusp for 7.4±3 mm, significantly less than for the RCC. The posterior portion of the LCC is not in direct contact with LV myocardium but apposes the left fibrous trigone (LFT), a tough membranous region joining the aorta to the anterior leaflet of the MV (Figure 5A). Thus, a catheter positioned in the antero-lateral portion of the LCC will usually record a larger ventricular electrogram than atrial electrogram whereas a catheter positioned in the more posterior portion of this cusp will often record a larger atrial electrogram. The left main coronary artery ostium is located 15 to 20 mm above the nadir of this cusp (Figure 3C and 3D).

The histological characteristics of the ASCs differ at their attachment to the LV ostium (Figure 4). At the base of the RCC, the LV myocardium is closely apposed to the aortic wall with myocardial fibers that run parallel to the base of the cusp (Figure 4A). In contrast, the LCC is separated from the LV myocardium by a tough band of fibrous tissue interspersed with strands of ventricular myocardium (Figure 4B). The NCC is in contact with loose connective tissue surrounding the interatrial septum (Figure 4C). These anatomic features are probably responsible for the differences in the electrogram recordings from the 3 cusps. Because of the semilunar nature of the attachments of the ASCs, there are 3 triangular extensions of the aortic root (interleaflet triangle) that reach to the level of the sinutubular junction of the aorta (Figure 4B). Those extensions are bound by the thin fibrous walls of the aorta between the expanded sinuses. The LV myocardium below the junction of the LCC and RCC (L-RCC) can be a source of VAs, though the true junction of these cusps is located ≈1 cm above the base of either cusp. Although VAs can be ablated either above or below the aortic valve, it is the myocardium of the LV ostium that is the target for ablation.
The NCC forms the posterior and right lateral portion of the anterior division of the LV ostium (Figures 2 and 3B). The NCC forms a direct continuum with the anterior leaflet of the MV at the intervalvular trigone, which demarcates the anterior from posterior divisions of the LV ostium (Figures 1, 2, and 3A). The most inferior portion of the NCC is in contact with the membranous portion of the interventricular septum where it comes in close apposition to the penetrating bundle of His (Figure 5A). Because of this close proximity, a catheter recording His bundle (HB) activation across the tricuspid annulus marks the inferior extent of the NCC. At approximately its midpoint and slightly more superiorly, the NCC is attached to the interatrial septum (Figure 3A and 3B). Therefore, a catheter positioned in the NCC usually records a large atrial electrogram and a much smaller far-field ventricular electrogram. The 3 ASCs are in direct contact a mean of 13.5 ± 1.8 mm above the base of the cusps where apposition in diastole is reinforced by the triangular nodule of Arantius.

The Posterior Division of the Aorto-Ventricular Membrane Within the LV Ostium

The posterior division of the aorto-ventricular membrane occupies ≈2/3 of the surface area of the LV ostium (Figures 1 and 2). The 4 components of the posterior division of this membrane includes (1) the MV (the central portion), (2) intervalvular trigone, (3) LFT, and (4) subvalvular segment of the aorto-ventricular membrane (Figure 5A and 5B). The left side of the anterior leaflet of the MV is joined to the LCC by a triangular membrane, the LFT, whereas the right side of that is joined to the NCC at the right fibrous trigone (Figure 2). Rather than forming a true annulus fibrosus, fibrous extensions of the aorto-ventricular membrane attach to the LFT and right fibrous trigone (ilia of Henle). The MV is anchored to the aorto-ventricular membrane rather than directly to the LV (Figure 2). Because the left atrium attaches to the aorto-ventricular membrane central to the periphery of aorto-ventricular membrane overlaying the LV ostium (Figure 5A), there is a portion of this membrane that lies between the MV and LV myocardium (Figures 2 and 5B). Thus, the tip of a catheter must be positioned beneath the MV, between the valve and myocardium, to directly contact the LV ostium. The posterior leaflet of the MV forms the most posterior portion of the aorto-ventricular membrane.

Clinical Presentation of VAs Originating From the LV Ostium

Thirty-one percent of all idiopathic VAs and 78% of idiopathic VAs originating from the LV occurred from the LV ostium. Thirty-one percent of all idiopathic VAs and 78% of idiopathic VAs originating from the LV occurred from the LV ostium.
ostium in one case series. Those VAs were mapped to the aortic root and LV epicardium adjacent to the LCC in 68%, aorto-mitral continuity (AMC, defined as the ventricular myocardium in contact with the LFT) in 16%, and MA in 16%. In our case series, the prevalence of idiopathic LV ostial VAs was similar (27% of all idiopathic VAs and 72% of idiopathic LV VAs). These LV ostial VAs arose from the aortic root in 53%, LV epicardium (within the great cardiac vein [GCV] and junction between the GCV and anterior interventricular vein) in 13%, AMC in 11%, and MA in 23%.

Right ventricular outflow tract (RVOT) VAs occur more frequently in women than men, although men consistently predominate with LV ostial VAs. Premature ventricular contractions have been more common than ventricular tachycardias.

Electrocardiographic Characteristics

Differentiation From the Right Ventricular VAs

The location of VA origins in the LV ostium may be predicted by the ECG (Figure 6). The transition zone in the precordial leads may be helpful for differentiating the site of origin in the right or left ventricle. MA VAs with an early transition (<V2) are easily distinguished from right ventricular VAs. However, LV outflow tract (LVOT) VAs arising from the aortic root, AMC, and GCV are often difficult to be distinguished from right ventricular VAs by the ECG alone. The R wave duration and R/S amplitude ratio in leads V1 and V2, and presence of S waves in lead I may be helpful for differentiating the VA origins in the aortic root or RVOT. However, those algorithms may not help to distinguish VA origins in the RCC and NCC or right ventricular HB region.

Differentiation From the Other LV VAs

VAs arising from the left posterior or anterior fascicle and posterior papillary muscle are located at the middle LV whereas LV ostial VAs are located at the LV base, allowing those to be readily differentiated by the ECG (Figure 6). For example, VAs arising from the middle LV almost always exhibit an rS pattern in lead V6 whereas...
most LV ostial VAs do not.\textsuperscript{6,7} In our case series, comparing the origins in the LV ostium with those from the middle LV, an absence of an rS pattern in lead V6 predicted an LV ostial origin with a high predictive accuracy (Table).

The Site-Specific Electrocardiographic Characteristics of the LV Ostial VAs

The site of VA origin in the LV ostium may be suggested by such electrocardiographic characteristics as S waves in lead V6, R waves in lead I, the ratio of the R wave amplitude in leads II and III (III/II ratio), “notching” of the late phase of the QRS complex in the inferior leads and the QRS polarity in the inferior leads.\textsuperscript{6,7,11,21} The predictive accuracy of these electrocardiographic characteristics in our case series are summarized in the Table. The presence of R waves in lead I was of low predictive value for differentiating aortic root VAs from MA VAs. A notch in the late phase of the QRS complex in the inferior leads, which may result from a phased excitation from the LV free wall to right ventricle (RV),\textsuperscript{7} has been reported to be very specific for MA VAs, especially at the sites other than the posterior portion. A negative QRS polarity in the inferior leads is quite specific for a VA origin in the posterior portion of the MA but was never observed with a VA origin from other sites in the LV ostium. In addition, a qrS pattern in the right precordial leads may be highly specific for L-RCC VAs (Figure 7).\textsuperscript{9} An epicardial

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{Trichrome staining of histological sections through the midpoint of the RCC (A), LCC (B), and NCC (C; magnification ×12.5). At the base of the RCC, the LV myocardium (brown, white arrow) is closely apposed to the aortic wall with little intervening fibrous tissue (blue, black arrow). The LCC is joined to the LV with a large amount of dense fibrous tissue (left fibrous trigone, black arrow) separating the aorta from the LV myocardium; in addition, significant interstitial fibrosis separating myocytes (white arrow). Adipose tissue separates the base of the NCC from the right atrial tissue (red arrow; note that smaller myocytes with lighter brown cytoplasm compared with ventricular myocytes). Fibrous tissue is inconspicuous.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{The aortic root and mitral annulus. A, Cranial-superior view of the aortic root and MV with the LA removed. Note that the NCC and the anterior leaflet of the MV are in direct continuity. Interior lighting allows recognition of a thin triangular membrane (the interventricular trigone) between the NCC and the anterior leaflet of the MV. Note that the membranous interventricular septum lies just beneath the NCC and includes the penetrating bundle of His. Also note that the LA wall is in direct contact with the NCC. The LFT is at the junction of the MV and LCC. Thick fibrous membrane arises from the LFT and right fibrous trigone (RFT) to encircle the MV. The attachment of the LA is shown inside the circumference of the LV ostium. B, Cranial-superior view of the enlarged aortic root and MV. The arrowheads indicate the periphery of aorto-ventricular membrane overlying the LV ostium. Reproduced with permission from reference 2.}
\end{figure}
location with early activation within the GCV is suggested by a pseudodelta wave at the QRS onset.22 Pseudodelta waves are characteristic but not specific to MA VAs.6 Though pace mapping studies demonstrated that a QR pattern in lead V1 could predict AMC VAs,21 in our case series, the occurrence of this pattern was <50%. The QRS duration is generally shorter with an origin in the septal side than in the lateral side of the LV ostium.6,7,21

Electrophysiological Characteristics

Activation and Pace Mapping

In mapping of LV ostial VAs, both CS and HB catheters are very helpful for predicting the site of origin.7,17 The CS catheter should be advanced into the GCV to record ventricular activations along the MA. When a ventricular activation recorded from the CS catheter precedes the QRS onset or is earlier than that in the HB region, an LV ostial VA origin is suggested. Care should

Table. Sensitivity, Specificity, and Positive and Negative Predictive Accuracies of the Different QRS Morphologies for a Ventricular Arrhythmia Origin

<table>
<thead>
<tr>
<th>Subject</th>
<th>QRS Morphology</th>
<th>Site of Prediction</th>
<th>Sensitivity, %</th>
<th>Specificity, %</th>
<th>PPV, %</th>
<th>NPV, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>LV VAs</td>
<td>rS in lead V6</td>
<td>LV ostium</td>
<td>99</td>
<td>97</td>
<td>99</td>
<td>97</td>
</tr>
<tr>
<td>LV ostium VAs</td>
<td>III/II ratio &gt;0.9</td>
<td>L-RCC, LCC, AMC, GCV</td>
<td>96</td>
<td>79</td>
<td>93</td>
<td>86</td>
</tr>
<tr>
<td>LCC VAs and RCC VAs</td>
<td>III/II ratio &gt;0.9</td>
<td>LCC</td>
<td>100</td>
<td>69</td>
<td>84</td>
<td>100</td>
</tr>
</tbody>
</table>

AMC indicates aorto-mitral continuity; GCV, great cardiac vein; LCC, left coronary cusp; L-RCC, the junction between the left and right coronary cusps; LV, left ventricle; NPV, negative predictive value; PPV, positive predictive value; RCC, right coronary cusp; VAs, ventricular arrhythmias.
be given to the local ventricular activation time relative to the QRS onset at the right ventricular HB region. During VAs with an origin in the RCC and NCC, a local ventricular activation recorded from the HB catheter precedes the QRS onset. The HB catheter also can be a useful landmark for mapping within the RCC and NCC.11,12,17

When the electrocardiographic characteristics cannot completely exclude the possibility of right ventricular VAs, mapping in the RVOT and right ventricular HB region should be first performed. Activation mapping seeking the earliest bipolar activity or a local unipolar QS pattern during VAs is most reliable for identifying the site of origin. Pace mapping is helpful for MA VAs just as it is for RVOT VAs,1,6,7 but may be less helpful for aortic root VAs because pacing in the aortic root may not exactly reproduce the QRS morphology of the VAs16 or obtain myocardial capture despite the use of high pacing current.

Preferential Conduction and the Relevant Myocardial Fibers in the LVOT

The reason why pace mapping or some algorithms using electrocardiographic characteristics may be less reliable for LVOT than RVOT VAs may be explained by preferential conduction within the LVOT.16,23 Preferential conduction in the LVOT often leads to a discrepancy between the best pace mapping site and successful ablation site. As a result, the ablation is more accurately guided by recording the earliest site of ventricular activation during the VAs than pace mapping, which may identify the preferential breakout site but not the origin. In ≈25% of the patients with aortic root VAs, there was a localized preferential breakout site in the RVOT. The mechanism of this preferential conduction may be explained by anisotropic conduction between the aortic root origin and breakout site in the RVOT. However, multiple myocardial fibers traveling from the LVOT to the RVOT or other LVOT sites and the endocardial or epicardial surfaces may occur with preferential conduction.16,23,24 Because in our experience multiple breakout sites can often be recorded and the breakout site(s) may be wide, catheter ablation is most reliably accomplished by targeting the origin itself.16,23,24

The RCC and NCC VAs and Transseptal Conduction

Far-field ventricular electrograms reflecting the activity of origins in the RCC or NCC are often recorded in the right ventricular HB region.17 When far-field ventricular electrograms preceding the near-field ventricular electrograms are recognized during VAs, they may be an indicator of a VA origin in the RCC or NCC. However, in some VAs with an RCC or NCC origin, these far-field ventricular electrograms are difficult to recognize because the near-field ventricular electrograms overlap with them due to a relatively short transseptal conduction time.17 When the earliest right ventricular activation suggests an origin near the HB, mapping of the RCC and NCC is required to determine whether the origin is truly from the RV or whether earlier activation can be recorded in the aortic root to decrease the risk of inadvertent damage to the AV conduction system.

Characteristic Local Electrograms at the Successful Ablation Site

In >90% of the aortic root VAs5,25 and 40% to 80% of the MA VAs,6,7 a 2-component electrogram with the earliest deflection preceding the QRS onset of the VAs was recorded at the successful ablation site (87% of the aortic root VAs, 75% of the GCV VAs, and 62% of the MA VAs in our case series; Figure 7). The first component of the electrogram (prepotential) is usually the smaller and higher frequency potential that precedes the QRS onset whereas the second component is a larger potential and occurs simultaneously with the QRS onset. The mechanism of those prepotentials remains unknown. However, prepotentials may represent activation of myocardial fibers connecting the VA origin to the breakout site or the VA origin itself and the second potential the activation of the local myocardium at the breakout site. In some VAs, especially arising from the LCC, an isoelectric line has been observed between those 2 potentials (Figure 7), and in others, a fractionated electrogram has connected the 2 potentials.5–7,10,11,25 The extensive fibrous tissue present between the base of the LCC and LV myocardium may be less helpful for aortic root VAs because pacing in the LVOT than RVOT VAs may be explained by preferential conduction within the LVOT.16,23 Preferential conduction in the LVOT than RVOT VAs may be explained by preferential electrocardiographic characteristics may be less reliable for identifying the site of origin. Pace mapping in the RVOT and right ventricular HB region should completely exclude the possibility of right ventricular VAs, mapping of the RCC and NCC.11,12,17

Figure 7. Successful ablation site of the premature ventricular contractions (PVCs) originating from the L-RCC. The first beat is a sinus beat and the second one is a PVC. At the successful ablation site, 2 ventricular activation components and no atrial activations were recorded during sinus rhythm (left panel). The sequence of the 2 components was reversed during the PVCs. The aortogram showed that the ablation catheter was located in the L-RCC (mid panels). Note that the tip of the ablation catheter was positioned at the L-RCC by defLECT the loop of the ablation catheter in the LV cavity. The activation map during the PVCs revealed the earliest activation was at the L-RCC (right panel). ABL d (p) indicates the distal (proximal) electrode pairs of the ablation catheter; ABL uni, the distal unipolar electrode of the ablation catheter; AP, antero-posterior; LL, left lateral; LVOT, left ventricular outflow tract; RAO, the right anterior oblique view. The other abbreviations are as in previous figures. Reproduced with permission from J Am Coll Cardiol. 2008;52:139–147.
dium (Figure 4B) suggests that an insulated myocardial fiber may exist between the VA origin and breakout site which may have slow conduction properties. Such fibrosis appears to be less significant at the base of the RCC (Figure 4A). Interestingly, in our case series, a prepotential was never recorded at the successful ablation site in any AMC VAs. This finding may suggest that prepotentials may result from activation of a low mass of myocardial fibers surrounded by interstitial fibrous strands as can be seen in histological sections (Figure 4B). In sections through the LV ostium, the ventricular myocardium becomes progressively thinner closer to the aortic and mitral valves. These anatomic characteristics of the LV ostium may allow for an appearance of a prepotential in the VAs.

The local ventricular activation at the successful ablation site preceded the QRS onset by an average of 30 to 40 ms. In many of the LV ostial VAs, a local atrial electrogram, which was smaller than the ventricular electrogram, was recorded at the successful ablation site. However, in the NCC VAs, the local atrial electrogram is usually larger than the ventricular electrogram at the successful ablation site.

Catheter Ablation

General
Radiofrequency (RF) catheter ablation has been increasingly established as an effective therapy for LV ostial VAs. Endocardial RF ablation is usually successful, but ablation...
may be required within cardiac venous structures for GCV VAs and occasionally for MA VAs. Long-term follow-up is limited, but the recurrence rates are generally low. Though the success rates for the RF catheter ablation widely range from 60% to 100%, lower success rates may be limited to VAs with an origin in sites around the LCC, AMC, and GCV.

In an endocardial approach or epicardial approach via the cardiac veins or subxiphoid access, RF catheter ablation may be limited in those VAs because of the inaccessibility or high impedance within the venous system or because the VA origins are located intramurally, close to the coronary artery, or epicardially underneath a fat pad. Cryo-thermal ablation may be an alternative to RF ablation in cases with high impedance within the venous system or when the origin is located close to a coronary artery. Because the posterior portion of the RVOT is in close apposition to the LV near the aortic root, when catheter ablation has not been successful in the LVOT the RV should be carefully mapped before determining that an epicardial approach is required.

Angiography as a Guide to Catheter Ablation
For catheter ablation above the aortic valve, selective angiography of the coronary artery and aorta should be performed before ablation to avoid arterial injury and precisely define the location of the ablation catheter. RF ablation is applied under continuous fluoroscopic observation with an angiographic catheter positioned within the coronary artery. The outline of the ASCs and flow in the coronary artery are observed by hand injections of contrast every 15 seconds. An RF application should never be delivered within 5 mm of the coronary artery. In 2 case series without any complications, the average distance from the tip of the ablation catheter to the left or RCA ostium was 12.2 to 12.9 mm (range, 7.3 to 17.2 mm) and 9.2 to 10.5 mm (range, 8.3 to 18.1 mm), respectively.

The 3 ASCs can be readily identified during biplane aortography or coronary angiography. The LCC is most easily identified in the left anterior oblique projection where this cusp is on the far lateral aspect of the aortic root, leftward, and superior to the HB catheter (Figure 8A). The RCC usually requires coronary angiography in both the right anterior oblique and left anterior oblique projections for accurate identification of the cusp relative to the RCA ostium (Figure 8B). In the right anterior oblique projection, the ablation catheter is typically located anterior and inferior to the RCA ostium. In the left anterior oblique projection, the typical ablation site is more leftward in the cusp than the RCA ostium. The NCC is readily identified as the most inferior of the 3 cusps and by its close relation to the HB catheter. In the right anterior oblique projection (Figure 8C), a catheter in the NCC is posterior and inferior to the RCA ostium, just above the HB catheter. In the left anterior oblique projection (Figure 8C), the NCC is just superior to the HB catheter, well posterior to the RCA ostium. Intracardiac echocardiography may also be useful for identifying the site of the ablation catheter.

RF Catheter Ablation in the LV Ostium
In all case series with endocardial LV ostial VAs, standard RF ablation was performed with a high success rate. The target temperature for standard RF energy delivery in the ASCs may be lower than in the AMC and MA to prevent aortic valve damage as has been observed in animal studies (ASCs, target temperature: 55°C, 15 to 30 W; AMC and MA, target temperature: 55°C, 30 to 50 W). In our experience, an RF energy delivery in the ASCs with the same target temperature setting of 60°C and maximum power output of 50 W as in the AMC and MA, has never caused any complications.

In the GCV VAs, RF current delivery via the venous system is often limited by high impedance and may cause complications such as venostenosis, vein rupture, venous thrombosis, or damage to the adjacent coronary arteries. During catheter ablation within the GCV, simultaneous coronary angiography is essential. Although cryo-ablation may be safer than RF ablation in the venous system, clinical data regarding its efficacy in GCV VAs remain limited.

Complications
Because the LV ostium occupies the central portion of the heart, ablation in this region is in close proximity to important structures, raising concern for potential complications. The most serious complication is coronary artery injury with inadvertent application of RF current within the coronary arteries being potentially lethal. Because of this possibility it is essential that some form of imaging be used to ensure that the ablation catheter is not within or directly overlying a coronary artery. In addition, aortic or mitral regurgitation may occur as a result of mechanical trauma or RF current applied directly to valvular tissue. Although previous studies have reported very low complication rates, it should be emphasized that those reports generally have come from highly experienced centers with highly skilled personnel. Transient sinus bradycardia followed by transient complete AV conduction block has been observed during RF ablation within the RCC. RF energy delivery within the RCC may have a thermal effect on the anterior epicardial fat pad containing parasympathetic ganglia, resulting in vagal stimulation.

Conclusions
The LV ostium is a common site of origin for idiopathic VAs. Meticulous mapping of the RVOT, ASCs, GCV, and LV epicardial surface may be required to achieve successful catheter ablation of VAs arising from this structure.

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None.
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