The pulmonary veins (PVs) have been demonstrated to be the major source of the triggers of paroxysmal atrial fibrillation (AF). Since PV isolation (PVI) guided by circumferential mapping with a circular catheter was initially proposed by Haissaguerre et al, PVI techniques have evolved to improve the clinical results. Extensive left atrial (LA) catheter ablation around the PVs has recently been suggested to achieve a better clinical result. However, more extensive LA ablation may cause critical complications. Circumferential PVI targeting the PV antrum, the transitional area between the PVs and left atrium, has also been recently suggested to achieve better clinical results with fewer complications. The mapping and catheter ablation of the PV antrum is more challenging than isolation of the tubular PV ostium because the PV antrum is a large-diameter structure that joins the LA wall at an oblique angle. The purpose of this study was to investigate the dimensions and electrophysiological characteristics of the PV antrum region in patients who had undergone circumferential PV antrum ablation guided by a multielectrode basket catheter (MBC).

Methods

Patient Characteristics

The study population consisted of 55 consecutive patients (47 men, 58±10 years) with symptomatic paroxysmal AF refractory to 4±1 class I or class III antiarrhythmic drugs (not including amiodarone). The mean duration of paroxysmal AF was 5±4 years (1–15). The mean echocardiographic LA dimension was 35±5 mm (27–43) and mean left ventricular ejection fraction 66±9% (47–80). Two patients had a history of ischemic heart disease. Each patient gave written informed consent, and all antiarrhythmic drugs were discontinued for at least 5 half-lives prior to the study.

Electrophysiological Study

The transeptal procedure was carried out with intracardiac echocardiography guidance recorded with a 9-French transducer catheter (Boston Scientific, Natick, MA, USA) operating at 9 MHz. Catheterization into the LA was carried out with a 1-puncture and 2-sheath technique. One sheath was 8-French (St Jude Medical, AF Division, Minnetonka, MN, USA) for an ablation catheter and the other 8.5-
French (Soft Tip EP Sheath™, EP Technologies, Boston Scientific Corporation, San Jose, CA, USA) for a mapping catheter. Intravenous heparin was administered to maintain an activated clotting time of >300 s after the atrial transeptal catheterization. The PV antrum was defined as the funnel-shaped and dilated proximal portion next to the tubular PV, which blended into the LA posterior wall as observed on the selective PV angiogram (Fig 1).

**Circumferential PV Antrum Isolation**

Circumferential PVI targeting the PV antrum potentials of 3–4 PVs was carried out using a 31 mm MBC (Constellation™, EP Technologies, Boston Scientific Corporation) as previously reported. An MBC was introduced toward the distal PV and then pulled back as proximally as possible without dislodgement with fluoroscopic guidance until its most proximal electrodes were positioned at the PV antrum, which was identified by a selective angiogram (Fig 1). In principle, the MBC was positioned coaxially to the PV. However, it was positioned sequentially with its tip held at the same position along the antral circumference only when the MBC could not obtain good contact with the antral circumference, particularly in the anterior segment of the left PVs or septal segment of the right PVs. A total of 56 bipolar electrograms were recorded by the MBC during sinus rhythm (right PVs) or distal coronary sinus pacing (left PVs). When AF persisted during the electrophysiological study, internal cardioversion was used to restore sinus rhythm and an MBC recording of at least 1 beat was obtained during the appropriate rhythm above. For longitudinal PV mapping using an MBC, PV antrum potentials were defined as follows (Fig 2): (1) single sharp potentials formed by the total fusion of the PV and LA potentials around the PV ostium; and (2) single sharp potentials with a transverse activation pattern around the PV ostium. The transverse activation pattern was defined as the simultaneous activation recorded from neighboring electrode pairs along the spline. The position of an 8-mm tip ablation catheter was confirmed using an MBC navigation system (Astronomer™). Radiofrequency ablation with a target temperature of 55°C and maximum power setting of 40 W for 60 s was carried out circumferentially targeting the electrode pairs where the PV antrum potentials were recorded with the end-point being their elimination (Fig 3). Radiofrequency applications were also delivered to the gap between the targeted electrode pairs on the neighboring splines in order to produce a continuous radiofrequency lesion at the PV antrum. When potentials conforming to the definition of PV antrum potentials were observed from some electrode pairs on the same spline, the antrum potential recorded from the most proximal electrode pair was targeted. If a residual conduction gap was detected after the PV antrum ablation, additional radiofrequency applications to the PV side just next to the previous radiofrequency lesions were delivered. The final end-point of this ablation technique was the complete PV electrical disconnection and non-inducibility of AF during an isoproterenol infusion (2–4 μg/min) and burst atrial pacing (to a cycle length as short as 200 ms). When the right inferior PV (RIPV) was difficult to cannulate with an MBC, circumferential ostial ablation was carried...
Fig 2. Definition of the pulmonary vein (PV) antrum potentials. (A) A PV antrum potential (star) recorded from the right superior PV during sinus rhythm. Note that the PV antrum potential was a single sharp potential, which was formed from the total fusion of the PV potentials (PVPs) and left atrial (LA) potentials around the PV ostium. The white arrowheads indicate the right atrial potentials, yellow arrowheads the LA potentials, and red arrow the PVPs. (B) A PV antrum potential (star) recorded from the left superior PV during distal coronary sinus pacing. Note that the PV antrum potentials were single sharp potentials, exhibiting a transverse activation pattern around the PV ostium. The yellow arrow indicates the transverse activation pattern, and the red arrow the PVPs.

Fig 3. Pulmonary vein (PV) antrum isolation in a right superior PV. (A) Before ablation. A PV antrum potential (star), a single sharp potential, which was formed by the total fusion of the PV potential and left atrial (LA) potential was recorded from the multielectrode basket catheter (MBC) electrode pairs A and B4-5 (yellow stars) and C to H7-8 (red stars) during sinus rhythm. The yellow stars indicate the most distal ablation (PV antrum) site at the roof and the red stars the most proximal ablation (PV antrum) site at the other walls. (B) After the PV antrum ablation at the MBC electrode pairs G7-8 to D7-8. (C) After the circumferential PV antrum ablation. Note that all of the PV potentials and PV antrum potentials disappeared and only the right atrial and LA potentials were observed.
out while mapping with a deflectable circular catheter. No LA ablation such as a linear ablation of the mitral isthmus or ablation targeting complex fractionated electrograms was carried out.

Evaluation of the Dimension of the PV Antrum

The most distal and proximal electrode pairs along the MBC splines where radiofrequency ablation was carried out were identified (Figs 1–4). Because the 31 mm MBC consisted of 8 splines (A–H) with eight 1-mm electrodes and 2-mm spacing, the distance between the middle of 2 neighboring electrode pairs was 3 mm (Fig 5). When the most distal electrode pair at the ablation site was apart from the most proximal electrode pair at the ablation site by 2 (3, 4 and 5) electrode pair spaces, the longitudinal distance between those ablation sites was considered to be 6, 9, 12 and 15 mm (Fig 5). For example, when the ablation site was at electrode pairs 4–5 and 7–8, the longitudinal distance between the ablation sites was considered to be 9 mm (Figs 3, 4). When the longitudinal distance between the most distal and proximal ablation sites (Ld) was ≥6 mm, the PV antrum was defined as noncoaxial.

Follow-up

Follow-up was carried out at 2 weeks, 1 month and every month thereafter, using 24-Holter and cardiac recordings. All patients who reported symptoms were given an event monitor to document the cause of the symptoms. Computed tomography was carried out before and 3–4 months after the ablation procedure to assess the PVs for stenosis.

Statistical Analysis

Continuous variables are expressed as the group mean±1SD. Comparisons of continuous variables were analyzed with the use of the Student’s t-test. Categorical variables expressed as numbers and percentages in different groups were compared with a chi-square test. Statistical significance was selected at a value of p<0.05.
Results

Circumferential PV Antrum Isolation

MBC mapping was carried out in 55 left superior PVs (LSPVs), 55 right superior PVs (RSPVs), 51 left inferior PVs (LIPVs) and 43 RIPVs. Four left PVs with a common trunk in which an MBC could be positioned appropriately, were included in the group of LSPVs. In 6 of 12 RIPVs, in which the deployment of the MBC was impossible, PV mapping and ablation with a circular catheter was carried out. In another 6 of those 12 RIPVs, PV mapping was abandoned because of their small ostia. In all the PVs in which MBC mapping was available, PV antrum potentials were observed around the circumference of the PV antrum. The PV antrum potentials were observed at sites limited by anatomical structures, such as the ridge of the LA appendage or indentation of the wall at the PV-LA junction around the circumference of the PV antrum, other than at the posterior wall of each PV, the roof of the LSPVs and anterior wall of the right PVs. After circumferential PV antrum ablation, a PV antrum electrical disconnection was achieved in 77% and a residual PV conduction gap through the previous ablation line was observed in 23% of all the targeted PVs. All of the residual PV antrum conduction gaps were eliminated by a mean of 3±2 min of local radiofrequency deliveries and the electrical disconnection of all targeted PV antra was successfully completed.

Dimension of the PV Antrum

The results of the dimension of the PV antrum are shown in Fig 6 and Table 1. In 31 of 55 (56%) LSPVs, 23 of 55 (42%) RSPVs, 32 of 51 (63%) LIPVs and 24 of 43 (56%) RIPVs, a noncoaxial PV antrum was identified. The LIPVs (63%) had a significantly higher incidence of a noncoaxial PV antrum than the RSPVs (42%) (p<0.05). In the LSPVs with a noncoaxial PV antrum, the incidence of the most distal PV antrum was significantly smaller in the roof than in the anterior wall (p<0.01) and bottom (p<0.0005) and the incidence of the most proximal PV antrum was significantly larger in the roof than in the bottom (p<0.005). In the RSPVs with a noncoaxial PV antrum, there were no significant differences in the findings of the most distal or proximal PV antra among the PV antrum locations. However, the anterior wall was less likely to be located at the most proximal PV antrum.

Table 1 The Dimension and Electrophysiological Characteristics of the PV Antrum

<table>
<thead>
<tr>
<th></th>
<th>LSPV (n=55)</th>
<th>RSPV (n=55)</th>
<th>LIPV (n=51)</th>
<th>RIPV (n=43)</th>
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<td>Non-coaxial</td>
<td>Coaxial</td>
<td>Non-coaxial</td>
</tr>
<tr>
<td></td>
<td>(n=24 [44%])</td>
<td>(n=31 [56%])</td>
<td>(n=32 [62%])</td>
<td>(n=32 [63%])</td>
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<td></td>
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<td>Non-coaxial</td>
<td>Coaxial</td>
<td>Non-coaxial*</td>
</tr>
<tr>
<td></td>
<td>(n=19 [37%])</td>
<td>(n=19 [44%])</td>
<td>(n=19 [44%])</td>
<td>(n=44%)]</td>
</tr>
<tr>
<td>PV diameter, mm</td>
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<td>21.1±2.8</td>
<td>19.2±2.1</td>
<td>18.3±2.4</td>
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<tr>
<td>Successful isolation, n (%)</td>
<td>24 (100%)</td>
<td>31 (100%)</td>
<td>32 (100%)</td>
<td>19 (100%)</td>
</tr>
<tr>
<td>RF duration, min</td>
<td>22.7±7.9</td>
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<tr>
<td>RF energy, J</td>
<td>41,000±13,130</td>
<td>58,540±14,040</td>
<td>35,480±8,670</td>
<td>24,190±8,290</td>
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<td>Difference, mm</td>
<td>9.3±2.6</td>
<td>78±2.2</td>
<td>8.3±2.5</td>
<td>8.2±2.1</td>
</tr>
</tbody>
</table>

PV, pulmonary vein; LSPV, left superior PV; RSPV, right superior PV; LIPV, left inferior PV; RIPV, right inferior PV; RF, radiofrequency.

*p<0.05, **p<0.01, ***p<0.005–0.0005; *LSPV, LIPV vs RSPV p<0.05.
distal site (p=0.07). In the LIPVs with a noncoaxial PV antrum, the finding of the most distal PV antrum was significantly less likely in the posterior wall than in the anterior wall (p<0.0001), roof (p<0.005) and bottom (p<0.0001) and the finding of the most proximal PV antrum was significantly greater in the posterior wall than in the roof (p<0.05) and bottom (p<0.0005). In the RIPVs with a noncoaxial PV antrum, the location of the most distal PV antrum was significantly more likely in the roof than in the anterior wall (p<0.0001), posterior wall (p<0.0001) and bottom (p<0.0001) and the most proximal PV antrum was significantly less likely in the roof than in the anterior wall (p<0.0001), posterior wall (p<0.0001) and bottom (p<0.0001).

As compared to the Ro in the PVs with a coaxial PV antrum, the finding of an Ro of ≥9 mm was much more likely in the LSPVs than in any other PVs and the Ro was significantly longer in the LSPVs than in the RIPVs (9.3±2.6 vs 7.8±2.2 mm; p<0.05).

Coaxial vs Noncoaxial PV Antrum

In each PV, the duration of the radiofrequency energy deliveries and total energy to complete the electrical disconnection of the PV antrum were significantly greater in the PVs with a coaxial PV antrum than in those with a noncoaxial PV antrum [p<0.0002] and 58.54±14.04 vs 41.00±1.10 J [p<0.0001], RIPVs; 23.9±6.3 vs 19.8±4.0 min [p<0.005] and 43.61±13.930 vs 35.480±8.670 J [p<0.05], LIPVs; 18.8±6.9 vs 14.5±5.5 min [p<0.05] and 33.3±12.990 vs 24.190±8.290 J [p<0.01], and RIPVs; 20.0±8.8 vs 13.2±5.5 min [p<0.01] and 33.7±20±14.910 vs 25.210±11.120 J [p<0.05]). In each PV, there were no significant differences in either the PV diameter or rate of a successful electrical disconnection of the PV antrum between the PVs with a coaxial PV antrum and those with a noncoaxial PV antrum.

Follow-up

During the follow-up period (16±5 months), 46 (84%) patients were free of symptomatic paroxysmal AF without any antiarrhythmic drugs after the first procedure. Two (4%) patients were free of symptomatic paroxysmal AF with one antiarrhythmic drug that failed to control the AF before the first procedure. No PV stenosis or spontaneous LA flutter was observed and there were no other complications.

Discussion

Circumferential PVI targeting the PV antrum has been recently demonstrated to achieve a greater than 80% cure of paroxysmal AF with few complications after one procedure.10, 11 Because the PV antrum may be a reliable target for PV ablation, it is important to know the electrophysiological characteristics of the PV antrum. Verma et al have developed a PV antrum isolation technique guided by intracardiac echocardiography and addressed the oblique nature of the antral-left atrium interface. However, detailed electrophysiological characteristics of the PV antrum are still unknown because the PV antrum is a large-diameter structure and thus, the circular catheter must be sequentially positioned as a “roving” catheter along each segment of the antral circumference to look for the PV potentials in that technique. An MBC that conforms to the contour from the PV ostium to the antrum because of its self-expanding splines could overcome the limitations of a circular catheter.12, 13 This study revealed the detailed electrophysiological characteristics of the PV antrum by direct 3-dimensional (D) mapping around the PV antrum with an MBC.

This study revealed the characteristic oblique shape of each PV antrum. In the LSPVs, the anterior wall and bottom were likely to be located at the most distal site and the posterior wall and roof at the most proximal site. In the RSPVs, the anterior wall was much less likely to be located at the most distal site and was likely to be located at the most proximal site. In the LIPVs, the anterior wall, roof and bottom were likely to be located at the most distal site and the posterior wall and roof at the most proximal site. In the RIPVs, the roof was most likely to be located at the most distal site and was much less likely to be located at the most proximal site. These results were consistent with the findings from another anatomical study.13 The anterior wall of the left PV antra was formed by the ridge of the LA appendage, and that wall was likely to be located at the most distal site. The bottom of the superior PVs and roof of the inferior PVs were formed by the carina between the ipsilateral PVs and the walls of the PV antra were likely to be located at the most distal site. The roof of the RIPVs and bottom of the inferior PVs could often be identified by indentations. However, the posterior wall of each PV antrum, roof of the LSPVs and anterior wall of the right PV antra were not limited by any anatomical structures. Those walls of the PV antra were generally located at the most proximal site. Verma et al have reported that the circular catheter must be advanced slightly because of the oblique nature of the antral-left atrium interface when mapping the anterior segments of the left PVs or the septal segments of the right PVs, which would correspond to a part of the roof in our division. Their findings were consistent with ours.

The 3-D geometry reconstructed from the image of the computed tomography or intracardiac echocardiography, or the magnetic resonance image, may be useful for evaluating the dimension of the PV antrum. However, during the actual case, the transeptal introduction of a mapping catheter may deform the PV antrum. Some PV antra may not be limited by any anatomical structures, especially in the LA posterior wall. Those PV antra must be determined by other parameters such as electrophysiological based ones. An electro-anatomic mapping may also be useful for evaluating the dimension of the PV antrum. However, that mapping technique using a single catheter may not be able to find the PV antrum potentials accurately because it is not suitable for longitudinal mapping. Therefore, we believe that this study provided more detailed and practically useful information about the PV antrum than analysis using those 3-D imaging or mapping devices.

This study demonstrated that a noncoaxial PV antrum was likely to render the PVI more difficult. That was probably because of a longer circumferential ablation line and difficulty with the sequential mapping due to the dimensional limitations. The anatomical complexity of the PV antrum may be a pitfall to the circumferential isolation technique. Some balloon catheters used to achieve PVI have been recently developed and those catheters may be desirable especially for the PVs with a noncoaxial PV antrum in aiming for a simple and effective procedure of PV ablation. The balloon configuration should be designed to fit not only a coaxial PV antrum but also a noncoaxial PV antrum. This study may provide the rationale for designing a new device such as a balloon catheter, which could complete PV antrum isolation in one energy application.

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Anatomy of PV Antrum and PV
Study Limitations

The border of the PV antrum can be defined as a continuous circumference only from the morphological findings obtained from the imaging maneuvers. Therefore, some physicians may challenge the concept of this study. However, the definitions obtained from the morphological findings often depend on the observer’s interpretation. In this study, PV antrum potentials were observed at PV antra, which were limited by anatomical structures. At other PV antra, the PV antrum potentials were observed continuously around the circumference connecting those anatomical structures. Therefore, we think that the PV antrum defined in this study was close to the anatomically defined one and less dependent on the observer’s interpretation.

Single, sharp potentials such as the PV antrum potentials defined in this study may be recorded elsewhere such as at the PV ostium or LA. However, the PV antrum potentials defined in this study may be a pitfall to the circumferential isolation technique.

In this study, every effort was made to position the MBC coaxially to the PV in order to evaluate the noncoaxial PV antrum. When the PV had an early branch, the MBC might be positioned coaxially to the main trunk of the PV. However, because few early branches were large enough to form a common ostium with the main trunk, we believe that the effect of the early branches on the determination of the long axis of the PV was not great enough to affect the results of this study.

Conclusions

The PV antrum was noncoaxial to the long axis of the PV in more than 50% of the PVs. This anatomical complexity may be a pitfall to the circumferential isolation technique. This study may provide the rationale for designing a new device such as a balloon catheter, which could complete a PV antrum isolation in one energy application.

References