Pulmonary Vein Anatomy in Patients Undergoing Catheter Ablation of Atrial Fibrillation
Lessons Learned by Use of Magnetic Resonance Imaging

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Background—This study sought to define the technique and results of magnetic resonance imaging (MRI) of pulmonary vein (PV) anatomy before and after catheter ablation of atrial fibrillation (AF).

Methods and Results—Twenty-eight patients with AF underwent ablation. Patients underwent gadolinium-enhanced MRI before and 6 weeks after their procedures. A control group of 27 patients also underwent MRI. Variant PV anatomy was observed in 38% of patients. AF patients had larger PV diameters than control subjects, but no difference was observed in the size of the PV ostia among AF patients. The PV ostia were oblong in shape with an anteroposterior dimension less than the superoinferior dimension. The left PVs had a longer "neck" than the right PVs. A detectable PV narrowing was observed in 24% of veins. The severity of stenosis was severe in 1 vein (1.4%), moderate in 1 vein (1.4%), and mild in 15 veins (21.1%). All patients were asymptomatic, and none required treatment.

Conclusions—This study demonstrates that AF patient have larger PVs than control subjects and demonstrates the value of MRI in facilitating AF ablation. The benefits of preprocedural MRI of PVs include the ability to evaluate the number, size, and shape of the PVs. MRI also provides an assessment of the severity of PV stenosis. (Circulation. 2003;107:2004-2010.)

Key Words: veins • lung • fibrillation • imaging • catheter ablation

Over the past 5 years, the technique of catheter ablation of atrial fibrillation (AF) using a “pulmonary vein” (PV) approach has emerged from being a highly experimental procedure to a procedure performed in many electrophysiology laboratories.1–6 PV stenosis has been identified as a unique complication of this procedure.7,8 Increasing evidence suggests that the risk of PV stenosis may be minimized and the success maximized by delivery of radiofrequency (RF) energy to the ostial portion of the PV.4–8 Investigational approaches to ablation that rely on balloon catheters are being explored.9,10

The importance of PV anatomy to the success of PV ablation is now appreciated. Magnetic resonance imaging (MRI) has the potential to provide accurate images and render 3D reconstruction for precise characterization of each PV. Although PV anatomy has drawn increasing attention from electrophysiologists, limited information exists concerning PV anatomy. Furthermore, no standardized methods for analyzing PV anatomy and assessing PV narrowing have been described. The purpose of this study, therefore, was to better define the techniques and results of MRI of PV anatomy in AF patients and control subjects (controls). Particular attention was focused on defining the size, shape, and anatomy of each PV and its relationship to other atrial structures. A second objective of this study was to report the incidence, severity, and characteristics of PV narrowing.

Methods

Patient Population

The study population consisted of 28 consecutive patients (22 men; age, 51 ± 14 years) who underwent ablation of AF by use of a PV approach and in whom MRI was obtained. Each patient had symptomatic drug-refractory paroxysmal AF. The median number of episodes of AF in the month before ablation was 30 (range, 1 to 200). The ejection fraction was 59 ± 6%. MRI was also performed in a control group of 27 patients (15 men; age, 47 ± 7 years) as part of a protocol approved by the Human Studies Institutional Review Board.

Electrophysiological Study and RF Ablation

All patients gave written informed consent for the ablation procedure. Catheter ablation of AF was performed according to the technique described by Haissaguerre et al.6

RF ablation was performed with an internally cooled tip ablation system (Chilli; Boston Scientific). Settings were as follows: maxi-
mum energy, 25 W for the inferior PVs, 35 W for the other veins, and target temperature 38°C. RF energy was applied proximal to the circumferential mapping catheter at those segments of the PV that revealed the earliest PV potentials. The end point of ablation at each PV was the elimination of PV potentials. Patients were followed up in the arrhythmia clinic. In the event of symptom recurrence, an event monitor was obtained.

Magnetic Resonance Imaging

Image Acquisition

All patients and controls underwent gadolinium-enhanced MRI with a 1.5-T MRI system (Signa Horizon LX; GE Medical Systems) with a body coil or a torso phased-array coil. All MRI scans were obtained during sinus rhythm. Magnetic resonance angiograms (MRAs) were obtained with a breath-hold 3D fast spoiled gradient-echo imaging sequence in the coronal plane. The acquisition time was 15 seconds. Maximum intensity projection (MIP) and multiplanar reformations were performed to reconstruct images of the PV and left atrium (LA). Virtual endoscopic images (VEIs) were also reconstructed for determining ostium location and early branching of PVs.

Measurement of PV and LA Dimension

Initial evaluation of the MRI scans was performed with 20- to 40-mm-thick MIPs and VEIs (Figure 1). The superoinferior (SI) and anteroposterior (AP) diameters of each PV were then assessed in 8- to 10-mm-thick slices of 2 long-axis MIP PV images (oblique coronal and oblique axial images). The slice thickness was selected because it usually covered more than half of the maximal PV diameter. To determine the long axis of the PV, axial and coronal tomograms at the junction of the PV and LA were displayed, and then oblique coronal and oblique axial images were identified parallel to each PV (Figure 2). The PV ostium was defined as the point of inflection between the LA wall and the PV wall. The ostium of right superior PV (RSPV) was difficult to detect because of its funnel shape. To overcome this obstacle, multiple oblique coronal planes were used for detecting the upper wall of the right inferior PV (RIPV) as a marker of the border between the LA and PV. The diameter of each PV was assessed at the ostium and 5, 10, and 15 mm more distal.

The size of the LA was measured according to the technique of Ho et al. The measurement of transverse diameter of the LA was defined as the distance between the midpoint of the right and left sides of the PVs in oblique axial images. The AP and longitudinal diameters were measured at the midpoint of the transverse diameter in oblique axial and sagittal images (Figure 2). Diameters were measured to the nearest millimeter. Intraobserver and interobserver variabilities of the MRI PV measurements were determined by having each scan reread by the initial reader in a blinded fashion and by having the scans read by a second blinded reader.

Assessment of PV Stenosis

Among the 28 patients in this series, 23 underwent MRA 6 weeks after ablation. A PV stenosis was defined as narrowing of the PV diameter ≥3 mm (the nominal resolution of the source images was 2.4 mm). The stenosis length and percentage diameter reduction were recorded. The severity of stenosis was categorized as mild (<50% stenosis), moderate (50% to 70%), or severe (>70%). The oblique coronal view was used primarily for measuring narrowed PV segments.

Statistical Analysis

All data are given as mean±SD. We used a Student’s t test for comparison between AF patients and controls. Comparisons of
values among 4 major PVs were made by 1-way ANOVA. If any significant differences were detected, further comparison between each group was made with a Student’s t test with Bonferroni correction. Comparisons between SI and AP diameter for each PV were made by Student’s t test. A level of P < 0.05 was considered statistically significant. The intraobserver variability of MR measurements of PV size was 0.9 ± 0.8 mm, and the interobserver variability was 1.3 ± 1.2 mm.

Results

Clinical Outcome of Catheter Ablation
All PVs (n = 110) were successfully imaged with contrast venography. Catheter ablation was not performed in the right middle or anomalous right upper PVs because of their small diameters. Electrical isolation was achieved in 86 of 86 targeted veins (100%). The number of RF applications per PV was as follows: left superior (LS) PV, 7.6 ± 5.4; left inferior (LI) PV, 6.2 ± 5.0; RSPV, 5.1 ± 3.7; and RIPV, 3.4 ± 3.1. The mean RF energy applied per vein was 15,399 J. The only complication that occurred was pericardial tamponade in 1 patient. During 8.3 ± 3.8 months of follow-up, 19 patients (67%) were free of AF without antiarrhythmic therapy, and 5 patients (19%) were free of AF with antiarrhythmic therapy. No patient had symptoms of PV compromise.

MRI

PV Anatomy
The LA and PV anatomy was visualized in each patient and control. Shown in Figure 1 is a representative MRI scan of a patient with typical PV anatomy. The orifices of the left PVs are located more superiorly than those of the right PVs. The RSPV and the LSPV project forward and upward, whereas the RIPV and LIPV project backward and downward. The trunk of the RIPV projects horizontally. The RSPV lies just behind the superior vena cava or right atrium, and the left PVs are positioned between the LA appendage and descending aorta. The orifice of the LA appendage lies in close proximity to the ostium of the LSPV.

Figure 3. Branching pattern of PV anatomy in AF patients and controls. Shaded portions indicate different parts from typical anatomy. A, Typical branching pattern. B, Short common left trunk. C, Long common left trunk. D, Right middle PV. E, Two right middle PVs. F, Right middle PV and right “upper” PV.

Figure 4. Examples of unusual PV anatomy. Long left common trunk (A, AP view; B, axial view) and right middle with discrete ostium (C, AP view; D, VEI). Character of ostium was detected easily in VEI.

Figure 5. A, Distribution of SI diameters of PV ostia in AF patients (solid circles) vs controls (open circles). No difference was observed between sizes of 4 PV ostia. Shown also are mean ± SD values. B, Comparison of distance from ostium to 1st branch between right and left PVs in AF patients vs controls. Distance is shorter in right-side PVs.
No differences in the patterns of PV anatomy were present in the AF and control groups (Figure 3). Typical PV anatomy, with 4 distinct PV ostia, was present in 16 patients and 18 controls. The second most common pattern was the presence of a short common left trunk, observed in 7 patients and 5 controls. This pattern differed from typical PV anatomy in that the junction of the lower wall of the LSPV and upper wall of the LIPV lies outside the LA rim. A third pattern of PV anatomy was the presence of a long common left trunk in 2 patients and 2 controls (Figure 4, A and B). Additional patterns that were observed involved abnormalities of pulmonary venous drainage of the right lungs with either a right middle PV (Figure 4, C and D), 2 right middle PVs, or a right middle and a right "upper" PV (an anomalous vein distinct from the RSPV).

The distribution in the size of the PV ostia in the SI dimension is shown in Figure 5A and the Table. No difference was observed in the size of the 4 PV ostia in AF patients. In contrast, the LIPV was smaller than the RIPV in controls (3.1 mm; RIPV, 3.3 mm; LIPV, 3.0 mm; P<0.0001). No difference was observed in the ratio of the SI diameter of each PV ostium to the LA longitudinal diameter in AF patients (RSPV, 0.28±0.05; LSPV, 0.29±0.04; RIPV, 0.29±0.04; and LIPV, 0.28±0.04) or in controls (RSPV, 0.30±0.05; LSPV, 0.31±0.05; RIPV, 0.32±0.05; and LIPV, 0.29±0.03).

The distance between the center of the RSPV and LSPV ostium was 48.2±9.2 mm in AF patients and 41.6±7.3 mm in controls (P<0.005, Figure 1). The distance between the RIPV and LIPV ostia was 54.6±7.5 mm in AF patients and 47.2±5.8 in controls (P<0.0001). The distance between the center of the RSPV and that of RIPV was 13.4±9.2 mm in AF patients and 10.5±2.1 in controls, and the distance between the center of LSPV and LIPV was 8.3±2.7 mm in AF patients and 7.4±3.4 in controls (right versus left, P<0.0001 in the AF group and P<0.001 in controls). A close relationship exists between the ostia of the 2 right and the 2 left PVs, with only several millimeters of atrial tissue between them (Figure 1). The distance between the LSPV and the LA appendage was 4.6±1.0 mm.

Incidence and Characteristics of PV Narrowing

Figure 6 shows the changes in PV diameter that were obtained before and 6 weeks after catheter ablation. Among the 71 ablated PVs evaluated with follow-up MRI, a detectable (≥3 mm) decrease in PV diameter was found in 17 (24%). The resultant severity of stenosis was categorized as
severe in 1 vein (RSPV, 1.4%), moderate in 1 vein (LIPV, 1.4%), and mild in 15 veins (6 LSPVs, 5 RSPVs, 3 LIPVs, and 1 long left common trunk; 21.1%). The average length, minimum diameter, and reduced diameter of narrowed segments were 15.0±5.1, 10.4±3.0, and 5.0±2.2 mm in patients with mild and moderate narrowings and 14.3, and 9 mm in the patient with a severe stenosis, respectively. None required treatment. Figure 7 shows examples of eccentric (A) and concentric (B and C) PV narrowing. An eccentric narrowing was seen in 6 PVs and was usually distal to the PV ostium. A concentric narrowing was seen in 11 PVs and typically involved the ostium.

No difference was observed in the number of RF applications or the applied energy and the development of PV stenosis (7.6±5.3 versus 5.5±4.5 applications and 14 514±11 249 versus 21 029±15 907 J, respectively, P>0.1).

Discussion

Major Findings

The purpose of this study was to evaluate PV anatomy before and after RF ablation by use of MRI. This study produced several important findings. First, the results reveal a very close proximity between the ostia of the right PVs and the ostia of left PVs. In addition, the mouth of the LSPV is separated from the LA appendage by only a thin rim of tissue. Second, PV anatomy is highly variable, with 38% of patients demonstrating variant anatomy. Third, the diameters of the 4 PVs do not differ, and there is little variation in the size of the PVs within a given patient. Fourth, PV and LA sizes are larger in AF patients than controls. Fifth, the left PVs have a longer “neck,” with a greater distance between the ostium and the first branch, than the right PVs. Sixth, PV ostia are oblong, with the SI diameter significantly greater than the AP.
diameter. And finally, RF ablation targeted immediately outside the PV ostia results in a detectable PV narrowing in 24% of PVs. Moderate or severe PV stenoses are rare, with each occurring in <2% of PVs.

**PV Anatomy and Size**

Remarkably little has been published concerning normal PV anatomy.11–14 Nathan and Eliakim12 are credited with first drawing attention to the myocardial PV sleeves, in a study of 16 postmortem human hearts. No data are provided on the precise size of either the PVs or the frequency and distribution of abnormal anatomic patterns.12 Another study of 26 human hearts reported that the mean longitudinal, AP, and transverse dimensions of the LA are 4.5±1.4, 3±0.8, and 4±1.2 cm, respectively.11 This study reported no difference in the diameter of the 4 PVs, with mean ostial diameters ranging from 1.0±0.2 to 1.2±0.2 cm. Variant anatomy was reported in 6 of the 26 hearts (23%). Using contrast venography, Lin et al13 were the first to specifically evaluate PV size in patients with AF. The results of this study revealed that the diameters of the RSPV and LSPV were greater than the diameter of the inferior PVs. In a subsequent article, these authors used MRI to evaluate PV anatomy and reported that the RSPV and LSPV were larger than the inferior PVs and that the superior but not inferior PVs were larger in diameter in patients with AF.14

The results of the present study provide clinically important new information concerning PV anatomy in AF patients and controls. In addition to providing detailed information regarding the dimensions of the human atrium and the size and shape of the PVs, our results reveal the relationship of these structures to the LA appendage and the frequency and patterns of variant PV anatomy. The 38% frequency with which variations in PV anatomy were observed is considerably greater than the 23% incidence of variant anatomy reported previously.11 This difference probably reflects the inclusion of a previously unreported anatomic variant in our study, which we refer to as a short common left trunk (observed in 15% of patients). This pattern differs from normal anatomy in that the junction of the LSPV and LIPV lies outside the LA wall. The remaining 18% of patients with variant anatomy demonstrated more marked anatomic variations. The precise dimensions of the PV ostia, the absence of a difference in the size of superior versus inferior PVs in AF patients, and the consistently greater size of PVs in AF patients than controls stands in contrast to the previous studies that have evaluated PV size.13,14 We suspect that these differing results reflect differences in technique. In this study, extreme care was taken to precisely define the location of the PV ostium using multiple planes. We suspect that this detailed analysis also allowed us to detect, for the first time, the oblong shape of the PV ostium. No previous study has reported data concerning the distance to the first pulmonary venous branch or data concerning the variation in PV size within patients.

**Incidence of PV Stenosis After RF Catheter Ablation**

The importance of PV stenosis has been highlighted by several case series.6,7 There have been no prospective studies that have performed a quantitative analysis of PV size and shape before and after ablation. The present study reveals that a decrease in PV diameter is not uncommon, occurring in 24% of PVs. Fortunately, the resultant severity of the stenosis was moderate (50% to 70% narrowing) or severe (>70% narrowing) in <2% of PVs, respectively. It is notable that PV stenosis was observed well within the PVs despite attempts to deliver RF to the “ostial” portion of the PV. No patient developed symptomatic PV stenosis. The low frequency with which significant PV stenosis was observed is consistent with a recent report that used computed tomography (CT) to evaluate PV stenosis.5

**MRA for Imaging PVs**

The results of this study reveal that MRI is useful in the evaluation of PV anatomy. In this study, the LA and PVs were visualized successfully in each patient. The intraobserver and interobserver reproducibility of PV measurements was excellent. It was reported previously that spiral CT and MRI are equally accurate in quantifying carotid artery stenosis and for the detection of small pulmonary embolism, although MRI had somewhat better results.15,16 Potential advantages of MRI include the absence of potentially nephrotoxic contrast medium and absence of radiation. From a clinical standpoint, it seems that either spiral CT or MRI can be used to define PV anatomy and to screen for stenoses after ablation. With the exception of patients who have implanted devices, local expertise within a given medical institution is likely to dictate which technique is used.

**Limitations**

This study has several limitations that must be considered. First, the number of patients who underwent AF ablation is small, which limits our ability to precisely define the incidence of PV stenosis. It should also be noted that follow-up MRIs were obtained only 6 weeks after ablation. We therefore could not evaluate the presence or absence of late progression of PV stenosis.

**Clinical Role of MRI for Catheter Ablation**

This study confirms the clinical value of MRI in facilitation of the ablation of AF arising from the PVs. Potential benefits of obtaining preprocedural MRI of the PVs include the ability to quantitatively evaluate the number, size, and shape of the PVs. This information is useful in selecting an appropriately sized circular mapping catheter and ascertaining that all PV orifices are evaluated during the procedure. Should a balloon-based procedure become a reality, this type of information is likely to be of even greater clinical importance. A second important role of MRI is its ability to provide a quantitative assessment of the location, shape, and severity of PV stenosis.

**Acknowledgments**

This study was supported in part by National Institutes of Health grant 1RO1-HL-64795.

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_Circulation_. 2003;107:2004-2010; originally published online April 7, 2003; doi: 10.1161/01.CIR.0000061951.81767.4E

_Circulation_ is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2003 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the World Wide Web at:
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