Detection of Inadvertent Catheter Movement into a Pulmonary Vein During Radiofrequency Catheter Ablation by Real-Time Impedance Monitoring

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Pulmonary Vein Impedance. ***Introduction:*** **During radiofrequency ablation to encircle or isolate the pulmonary veins (PVs), applications of radiofrequency energy within a PV may result in stenosis. The aim of this study was to determine whether monitoring of real-time impedance facilitates detection of inadvertent catheter movement into a PV.**

Methods and Results: **In 30 consecutive patients (mean age 53 ± 11 years) who underwent a left atrial ablation procedure, the three-dimensional geometry of the left atrium, the PVs, and their ostia were reconstructed using an electroanatomic mapping system. The PV ostia were identified based on venography, changes in electrogram morphology, and manual and fluoroscopic feedback as the catheter was withdrawn from the PV into the left atrium. Real-time impedance was measured at the ostium, inside the PV at approximately 1 and 3 cm from the ostium, in the left atrial appendage, and at the posterior left atrial wall. There was an impedance gradient from the distal PV (127 ± 30 Ω) to the proximal PV (108 ± 15 Ω) to the ostium (98 ± 11 Ω) in each PV (P < 0.01). There was no significant impedance difference between the ostial and left atrial sites. During applications of radiofrequency energy, movement of the ablation catheter into a PV was accurately detected in 80% of the cases (20) when there was an abrupt increase of ≥4 Ω in real-time impedance.**

Conclusion: **There is a significant impedance gradient from the distal PV to the left atrium. Continuous monitoring of the real-time impedance facilitates detection of inadvertent catheter movement into a PV during applications of radiofrequency energy.** *(J Cardiovasc Electrophysiol, Vol. 15, pp. 674-678, June 2004)*

pulmonary vein, impedance, left atrium, atrial fibrillation, catheter ablation

Introduction

With the recognition of the critical role that the pulmonary veins (PVs) play in the initiation and perpetuation of atrial fibrillation (AF),[1,2] catheter ablation to isolate or encircle the PV ostia has been performed to treat patients with AF. Accurate identification of the PVs and their ostia are key components of these ablation procedures[3-8] because inadvertent applications of radiofrequency energy within the PVs may cause PV stenosis[9] and because the PV ostia serve as important landmarks during both segmental ostial ablation and left atrial ablation procedures.[3,6,10]

Our observations suggested that impedance may be higher within the PVs than in the left atrium. The aim of this prospective study was to quantitatively analyze impedance measurements in the PVs and left atrium and to determine whether real time-impedance monitoring facilitates the accurate detection of inadvertent catheter movement into a PV during a catheter ablation procedure to eliminate AF.

Methods

Study Subjects

The subjects of this study were 30 patients (24 men and 6 women; mean age 53 ± 11 years) who underwent a catheter ablation procedure for treatment of AF. Among the 30 patients, 16 had paroxysmal AF and 14 had persistent AF. Mean left atrial diameter as determined by two-dimensional transthoracic echocardiography was 41 ± 6 mm. Mean left ventricular ejection fraction was 0.54 ± 0.05. Structural heart disease was present in 4 (13%) of the 30 patients.

Electrophysiologic Procedure

All patients provided informed written consent. An electrophysiologic procedure was performed in the postabsorptive state under conscious sedation, as described previously.[4,5] Therapy with all antiarrhythmic drugs except amiodarone was discontinued five half-lives prior to the study. A quadripolar electrode catheter (EP Technologies Inc., San Jose, CA, USA) was positioned within the coronary sinus and used for recording and atrial pacing. After transseptal catheterization, systemic anticoagulation was achieved with intravenous heparin to maintain an activated clotting time (ACT) of approximately 300 seconds. Angiograms of the PVs were performed in all patients to define the PV

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anatomy. Angiograms were performed in a 40° left anterior oblique projection for the left-sided PVs and in an antero-posterior projection for the right sided-PVs by hand injection of 10 to 12 mL of radiocontrast material and recorded digitally. A quadripolar, deflectable-tip, temperature-controlled, 8-mm-tip catheter (Navi-Star, Biosense-Webster, Diamond Bar, CA, USA) was positioned within the left atrium and was used for mapping and ablation under the guidance of an electroanatomic mapping system (CARTO, Biosense-Webster).[10] Bipolar intracardiac electrograms were filtered at bandpass settings of 30 to 500 Hz and recorded digitally (EPMedSystems, West Berlin, NJ, USA).

Computed Tomography

Computed tomography (CT) of the chest with three-dimensional reconstruction of the left atrium was performed in all patients 1 to 4 weeks before the procedure to define the left atrial geometry and PV anatomy and to identify morphologic variations such as a common ostium of the left-sided PVs or a right middle lobe PV.[9] CT was performed with a QX/i 16-row multidetector CT scanner (GE LightSpeed, GE Medical Imaging, Waukesha, WI, USA) with non-ionic intravenous contrast material, as described previously.[9] The resolution of the CT scans was 1.25 mm. The CT scans were repeated 2 to 4 months after the ablation procedure to determine whether PV stenosis had occurred. The diameter of a PV ostium was measured as the longest distance at the junction of the left atrium and the main trunk of the PV on three-dimensional reconstructions of the CT images using digital calipers exactly as described previously.[9]

Study Protocol

The study was conducted in three stages.

Identification of the PVs and their ostia

The left atrial shell was reconstructed using a three-dimensional electroanatomic mapping system (CARTO, Biosense-Webster) with a minimum of 75 geometry collection points. The left atrial appendage and the mitral annulus were carefully demarcated. Each PV was cannulated with the mapping catheter, and the mapping catheter was positioned within a distal portion of the PV, 3 to 5 cm from the ostium under fluoroscopic and CARTO guidance. The catheter then was withdrawn slowly into the left atrium. A tube was used to represent the approximate location of the main body of the PV. Because the tubes have a fixed diameter and may not accurately represent the size and location of the PV ostia, the mapping catheter was positioned within the proximal PV, and the ostium was defined and tagged according to the following criteria: (1) fluoroscopic location as determined by the venograms; (2) change in electrogram morphology, with the simultaneous presence of large atrial electrograms and PV potentials; and (3) manual and visual feedback as the catheter was withdrawn into the left atrial cavity.

The main criterion for the accurate identification the PV ostium was the angiographic location. However, because angiographic images of PVs may be foreshortened depending on the angle of projection, rotation of the heart within the chest cavity, and variations in the angle at which the PVs connect to the left atrium, ostial location was also confirmed by a change in electrogram morphology and manual and visual feedback. For example, the presence of only PV potentials without any atrial electrograms at the angiographic ostium may suggest a more distal ostial location. Therefore, the catheter was further pulled pack to the left atrium, and the site where the catheter fell into the left atrial cavity indicated the PV ostium.

Impedance measurements

Real-time impedance was measured between the tip of the 8-mm-tip mapping/ablation catheter and the ground patch positioned under the left scapula by a radiofrequency current generator (Stockert 70 RF, Biosense-Webster). Real-time impedance was measured at 10-μs intervals during continuous delivery of low-amplitude (2 μA), 50-kHz electrical current from the generator. Measurements were always made within the main trunk of all PVs. Impedance was measured within the PV at 3 and 1 cm from the ostium, at the ostium, in the left atrial appendage, and along the posterior left atrial wall. To determine the reproducibility of measurements, real-time impedance was measured at least five times at all test sites, including the posterior left atrium, left atrial appendage, PV ostia, and proximal and distal PVs in 10 patients. The mean coefficient of variation among all sites was 1.8 $\pm$ 1.5%. There was no difference in the coefficient of variation of impedance among the sites sampled.

Clinical utility

Because real-time impedance measurements indicated an impedance gradient from distal PV to the left atrium, the clinical utility of an impedance rise during application of radiofrequency energy in determining inadvertent catheter movement into a PV was tested during the last 10 ablation procedures. One of the investigators operated the CARTO system and was responsible for acquisition of the anatomic tags and was blinded to the real-time impedance measurements. Another investigator monitored the real-time measurement continuously during the ablation and was blinded to the CARTO images as well as to the fluoroscopic views; therefore, he was unaware of the anatomic location of the ablation catheter. Whenever the investigator operating the CARTO system noticed movement of the catheter into a PV, the impedance at that moment was recorded. Whenever the investigator monitoring the radiofrequency generator noticed an abrupt and persistent increase (>3 consecutive readings) in impedance, the location of the mapping catheter was noted and confirmed fluoroscopically and with the CARTO system.

During applications of radiofrequency energy, impedance was measured at 10-μs intervals using the main radiofrequency current (500 kHz) and was displayed five times per second. Because impedance is primarily determined by the resistive characteristics of the tissue through which the current travels and the surface area of the electrodes and is proportional to the voltage gradient and the current, higher current and voltage did not have an effect on initial impedance measurements. Because of the risk of PV stenosis, impedance measurements within a PV during radiofrequency energy applications were not feasible. However, the mean coefficient of variation during radiofrequency energy application at a fixed site within the left atrium was 4 $\pm$ 3%. The variation was primarily due to a decrease in impedance after onset of radiofrequency energy application.

Radiofrequency Catheter Ablation

Left atrial catheter ablation was performed to encircle the left- and the right-sided PVs 1 to 2 cm from their ostia, as described previously.[10] Ablation lines also were created in the posterior left atrium and in the mitral isthmus. Radiofrequency energy was delivered at a target temperature of 55°C and a maximum power output of 70 W for 20 to 40 seconds at each location.

Follow-Up

All patients were seen in an outpatient clinic 2 to 3 months after the ablation procedure and every 3 months thereafter. A repeat CT scan of the heart was obtained 2 to 4 months after the ablation procedure. Any decrease in PV diameter >70% was defined as PV stenosis.

Statistical Analysis

Continuous variables are expressed as mean ± 1 SD and were compared by Student's *t*-test. Categorical variables were compared by Chi-square analysis or Fisher's exact test. Comparisons of impedance measurements were performed with the paired *t*-test or analysis of variance (ANOVA) with repeated measures. Differences between groups of continuous variables were compared by ANOVA, and post hoc analyses were performed with the Newman-Keuls' test. $P < 0.05$ was considered statistically significant.

Results

Impedance at Distal, Proximal, and Ostial PV Sites

There was a progressive decrease in impedance as the catheter was withdrawn from the distal PV to the left atrium. Pooling the data obtained in the four PVs, the mean impedance was 127 ± 30 Ω in the distal PV, 108 ± 15 Ω in the proximal PV, 98 ± 11 Ω at the ostium, 92 ± 8 Ω at the posterior left atrial wall, and 97 ± 11 Ω within the left atrial appendage ($P < 0.01$, Fig. 1). There were no significant differences among the impedances measured at the PV ostia, left atrial posterior wall, and left atrial appendage.

Variability of Impedance Among the PVs

Among the four PVs, the distal and proximal PV impedances were highest in the right inferior PV and lowest in the right superior PV (Fig. 1). Except for the right superior PV, the impedance in the proximal PV was always higher than the ostial impedance.

Diagnostic Accuracy of an Impedance Gradient

In all PVs, an abrupt and persistent rise in impedance of ≥4 Ω had a sensitivity of 73% and a specificity of 100% for indicating a catheter position within the proximal PV. For catheter positions within the distal PV, the sensitivity and specificity were 93% and 100%, respectively. The positive and negative predictive values of a ≥4 Ω rise in impedance as an indicator of a proximal PV location were 100% and 79%, respectively; for a distal PV location, the positive and negative predictive values were 100% and 94%, respectively.

The positive and negative predictive values of a ≥4 Ω increase in impedance as an indicator of a proximal or distal

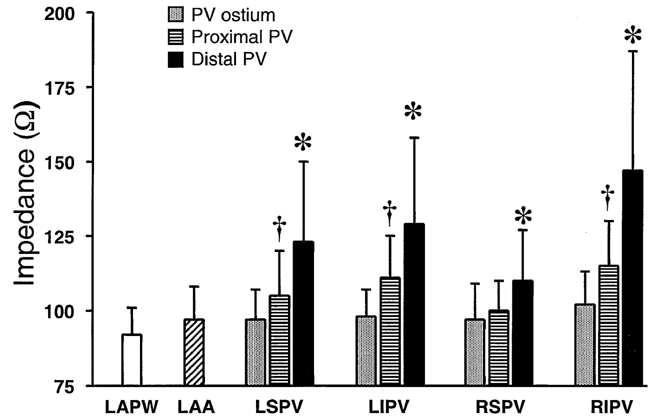

Figure 1. *Real-time impedance measurements. LAA = left atrial appendage; LAPW = left atrial posterior wall; LIPV = left inferior pulmonary vein; LSPV = left superior pulmonary vein; RIPV = right inferior pulmonary vein; RSPV = right superior pulmonary vein. *P < 0.05 for impedance within the distal PV compared to all other sites; †P < 0.05 for impedance within the proximal PV compared to ostial and left atrial sites.*

PV location were higher for the left superior, left inferior, and right inferior PVs than for the right superior PV (Table 1).

PV and LA Diameter, and Impedance

There was no correlation between the PV diameter and the impedance measured at the ostium and the proximal and distal PVs. Likewise, there was no relationship between left atrial size and PV impedance.

Validity of Impedance Measurements as a Guide During Ablation

During 90 applications of radiofrequency energy to encircle the ostium of a PV, 25 applications were aborted because of a ≥4 Ω rise in impedance (Fig. 2). In 25 (100%) of the 25 episodes, the ablation catheter was noted by fluoroscopy and the electroanatomic map to have moved at least 1 cm into the PV. Another 20 applications of radiofrequency energy were aborted because fluoroscopy and/or the electroanatomic map indicated that the ablation catheter had moved into a PV. With these 20 aborted applications of energy, there was a ≥4 Ω increase in impedance in 16 (80%). The four applications of energy that were not associated with an impedance rise were being delivered near the ostium of the right superior PV.

TABLE 1

Diagnostic Accuracy of an Impedance Gradient of 4 Ω Among the Pulmonary Veins

	Sensitivity	Specificity	PPV	NPV
LSPV	75%	100%	100%	80%
LIPV	83%	100%	100%	85%
RSPV	50%	100%	100%	33%
RIPV	85%	100%	100%	87%

LIPV = left inferior pulmonary vein; LSPV = left superior pulmonary vein; NPV = negative predictive value; PPV = positive predictive value; RIPV = right inferior pulmonary vein; RSPV = right superior pulmonary vein.

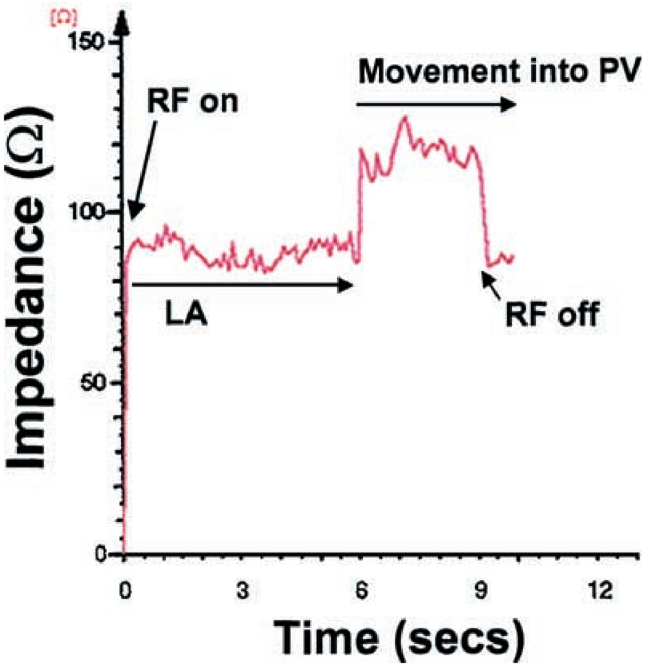

Figure 2. *Impedance rise during catheter movement into a pulmonary vein (PV). Impedance was continuously measured and displayed in a graph format during application of radiofrequency energy (RF) within the left atrium (LA) near the ostium of the left superior pulmonary vein. An abrupt rise in impedance indicated the inadvertent movement of the catheter into the pulmonary vein and was confirmed with fluoroscopy. Radiofrequency energy application was immediately aborted.*

PV Stenosis

During 185 ± 96 days of follow-up, none of the patients developed symptomatic PV stenosis. PV morphology was assessed by a repeat CT scan 82 ± 30 days after the ablation procedure, and no PV narrowing or stenoses >20% were observed in any of the patients.

Discussion

Main Findings

This study demonstrates that there is an impedance gradient between the distal PV and the ostium, and that impedance at the ostium is no different than the impedance measured when the mapping/ablation catheter is against the left atrial wall or in the left atrial appendage. Movement of the catheter from a site near the ostium to a site 1 cm or more within a PV usually was associated with a ≥4 Ω rise in impedance. The positive and negative predictive values of a rise in impedance as an indicator of movement of the catheter into a PV were 100% and 80%, respectively.

Impedance Within the PVs

Impedance within the PVs was found to be higher than at the ostium and the adjacent left atrium. Because impedance was measured continuously with a very low current, the higher impedance within the PVs cannot be attributed to the thermal effects of radiofrequency energy. Although the thermal effects of radiofrequency energy may result in changes in impedance after a critical core temperature is reached, this effect would only facilitate the detection of the impedance gradient that occurs during catheter movement into the PV because impedance within the PV would be even higher than at the ostium, where energy is being delivered and where there may have been a decrease in impedance. Because the PVs are surrounded by lung parenchyma, the current delivered from the tip of the mapping catheter encounters higher resistance as it travels to the grounding patch on the body surface. The resistive effect of the surrounding tissue also explains why the impedance is higher in the distal PV than in the proximal PV, because the distal PV is further within the lung parenchyma. Impedance in the atrium and ostium also may be lower because of a larger blood volume than within a PV. Blood is an excellent conductive medium and may contribute to lower impedance measurements within the atrium.

Right Superior PV

The impedance gradient between the ostium and the proximal PV was significantly smaller in the right superior PV than in the other PVs. Accordingly, the predictive value of an impedance rise to identify proximal versus ostial PV locations was lower for the right superior PV. These observations may be due to the complex anatomy of the right superior PV. The ostium and proximal segments of the right superior PV often have a funnel configuration.[11] Therefore, it may be difficult to identify the exact location of the PV ostium. Moreover, because the proximal segment of the PV is dilated and may appear "atrialized," it is possible that the impedance in this segment is lower. The right superior PV is also in close contact with the right atrium and superior vena cava, both of which may reduce the volume of adjacent lung tissue around the right superior PV. Therefore, the lower predictive value of impedance rise in the right superior PV may stem from imprecise identification of the proximal segment as the ostium and/or to the lower impedance measurements in the proximal segment of the PV compared to the other PVs.

Study Limitations

In this study, PV ostia were identified by integrating fluoroscopic, electroanatomic, angiographic, electrophysiologic, and CT scan data. Intracardiac echocardiography was not used.[8,12] It is possible that the ostia were not precisely identified for all PVs.

There may be several causes of a sudden rise in impedance during applications of radiofrequency energy. These include coagulum formation at the tip of the catheter, withdrawal of the catheter into a guiding sheath, or a fracture within the catheter. During this study, these phenomena were not observed during ablation around the PVs.

The patients in this study did not have any variants in PV anatomy, such as a right middle lobe PV or a left common PV. Therefore, it is not known whether the results of this study apply to these anatomic variants.

The absolute values for the impedance measurement may vary depending on the electrode size and the catheter system used; in this study, only an 8-mm-tip ablation catheter was used. The results may have differed if another type of ablation catheter had been used.

Conclusion

Although the optimal technique for catheter ablation of AF remains to be determined, it is important to avoid applications of radiofrequency energy within a PV regardless of the technique used. Continuous monitoring of real-time impedance facilitates the accurate detection of inadvertent catheter movement into the tubular portion of a PV during ablation. However, impedance measurements do not distinguish the PV ostia from the left atrium, and other methods are necessary for accurate definition of the PV ostia.

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