Pulmonary vein isolation (PVI) is the standard catheter ablation procedure for patients with recurrent, symptomatic, drug-refractory paroxysmal atrial fibrillation (AF). Hyperlinked to this article is a video that shows a PVI procedure performed at Brigham and Women’s Hospital, Boston, MA, with the use of image guidance from a cardiac magnetic resonance image obtained the day before the procedure, 3-dimensional electroanatomic mapping, fluoroscopy, and intracardiac echocardiography. An externally irrigated ablation catheter and a circular mapping catheter (Lasso Variable CMC, Biosense Webster Inc., Diamond Bar, CA) were placed through separate transseptal punctures. Major contraindications include the presence of a left atrial thrombus or inability to administer anticoagulation to cover a 30-day peri-procedural and post-procedural period.

Most often, PVI is achieved with the use of a tip electrode catheter, radiofrequency energy to make ablation lesions, and a mapping strategy to confirm isolation of pulmonary vein (PV) sleeves from the rest of the left atrium. Newer technologies are under investigation that promise to make PVI quicker, easier, and, it is hoped, safer. For instance, balloon catheters using various energy sources such as laser or cryothermy and circular, multielectrode catheters that allow radiofrequency energy to be delivered to multiple electrodes simultaneously are in various stages of development and regulatory approval.1 These technologies seek to reduce the number of applications necessary to achieve a circumferential conduction barrier around the PVs. A continued advantage of tip electrode catheters, however, is that the level of PVI is easily controlled by the operator, whereas lesion placement with balloon and multielectrode catheters is somewhat constrained by their shape and maneuverability. Currently, only an externally irrigated, tip electrode ablation catheter has been approved by the Food and Drug Administration for marketing in the United States for treatment of recurrent, symptomatic, drug-refractory paroxysmal AF.

PVI can be achieved by a segmental or circumferential approach. The segmental approach targets individual muscle sleeves that extend in fingerlike projections beyond the PV ostia and requires fewer lesions compared with the circumferential approach. Ablation within the PV ostia increases the risk of PV stenosis, which is largely avoided by the circumferential approach, in which the target is antral tissue outside of the PV ostia. A circumferential ablation strategy was compared with a segmental ablation approach and afforded greater freedom from recurrent atrial arrhythmia.2,4 One explanation for the superior results is that the greater volume of left atrial tissue encompassed in the circumferential lesion set may isolate potential AF triggers that reside in the PV antrum. PVI, however, can be more difficult and time consuming at the antral level.

**PVI Procedure**

**Preparation Before the Day of the Procedure**

In addition to adequately preparing the patient in terms of expectations about a catheter ablation procedure, the operator must decide whether preprocedural imaging will be useful and make decisions about the use of antiarrhythmic medication and anticoagulants.

Within our institution, preprocedural imaging is not a prerequisite for a PVI procedure, largely because of operator preferences. Preprocedural imaging may provide useful information on underlying cardiac disease, such as identification of a myocardial scar visualized with gadolinium late enhancement on magnetic resonance imaging. Magnetic resonance imaging or computed tomographic scanning will identify unusual anatomy such as a common vein ostium or accessory PVs. The anatomic shell obtained by computed tomography or magnetic resonance imaging can be merged with the electroanatomic shell created within the 3-dimensional mapping system to provide greater anatomic detail. Several reasons to consider foregoing preprocedural imaging include added cost, patient inconvenience, additional radiation exposure from computed tomographic scanning, and the possibility that intraprocedural imaging such as intracardiac echocardiography or rotational angiography may be an adequate replacement.

We usually discontinue class I or III antiarrhythmic drugs at least 5 elimination half-life periods before the procedure, except for amiodarone, which we try to discontinue ≥1 month before the procedure. Warfarin is generally continued throughout the procedure, a strategy supported by emerging data on its safety and efficacy.5-7 For patients in whom we discontinue warfarin, we frequently prescribe “bridging” subcutaneous enoxaparin 1 mg/kg injected twice daily for 2

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(Circulation. 2011;123:e596-e601.)

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Circulation is available at http://circ.ahajournals.org

DOI: 10.1161/CIRCULATIONAHA.110.990028
days before the procedure and 0.5 to 1.0 mg/kg after the procedure until the international normalized ratio (INR) is within the therapeutic range. Patients who have an INR of 2.0 to 3.5 during the procedure do not receive subcutaneous enoxaparin before or after the procedure; however, the operator must be prepared to reverse warfarin anticoagulation with fresh frozen plasma or recombinant factor VII in the event of serious periprocedural bleeding complications.6

Choice of Anesthesia
Patients are held to a nothing-by-mouth status after midnight the night before the procedure. We generally use moderate intravenous conscious sedation with a combination of fentanyl and midazolam. General anesthesia is reserved for patients who have had previous difficulty with intravenous conscious sedation or who have high-risk features that make intravenous conscious sedation less desirable, such as a Mallampati class 3 or 4 airway, severe sleep apnea, morbid obesity, or a history of severe drug-refractory gastroesophageal reflux. One caveat is that our institution provides trained anesthesiologists who are immediately available to assist in emergencies related to sedation. In our estimation, general anesthesia can be an advantage to limit unpredictable patient movement and respirations; however, we believe that this advantage may be superseded by an inability to immediately assess a patient for signs of stroke or cardiac tamponade, when the first indication may be patient restlessness or agitation. The use of general anesthesia has been associated with a higher risk of esophageal injury.8

Preparation the Day of the Procedure

Monitoring and Personnel
Patients are continuously monitored with ECG recording, nasal capnography, pulse oximetry, and blood pressure measurements every 5 to 10 minutes. Careful monitoring of these parameters and the patient’s level of sedation, along with airway management, is the responsibility of a nurse at the head of the table. Other laboratory personnel include a radiation technologist and a second nurse or technician during critical portions of the procedure.

Vascular Access
Patients are prepped and draped with the use of sterile surgical techniques. Access is obtained through the femoral veins. Rarely, we use subclavian or jugular vein access for a multielectrode catheter placed in the coronary sinus. Operators at other institutions prefer a femoral or radial arterial line for continuous blood pressure monitoring, but we are concerned about the potentially higher rates of groin complications. Each operator at our institution has a slightly different preference for the type and number of catheters used during the procedure. A multielectrode catheter in the coronary sinus is standard for recording and pacing. Optional configurations include additional electrodes in the right atrium. Some operators prefer a 20-pole catheter that can be looped along the right atrial free wall and tricuspid valve annulus with distal electrodes in the coronary sinus. We may place a quadripolar catheter in the His bundle recording position with an indifferent electrode in the inferior vena cava used for unipolar pacing. The use of intracardiac echocardiography is standard to aid transseptal puncture and provide visualization of key anatomic structures during the procedure. Depending on operator preference, we use phased-array or rotational echocardiography catheters. To accommodate these catheters, multiple femoral vein punctures are required, usually 2 per femoral vein.

Equipment
The various equipment choices for a PVI procedure are beyond the scope of this article, but we would like to discuss the advantages and disadvantages of some of the more commonly used pieces of equipment.

Circular Mapping Catheter
The CMC is a multielectrode (10 to 20 poles) catheter that has a preformed circular shape and is placed within the antrum or ostium of PVs to record PV potentials. One can more easily assess the disappearance of PV potentials and observe dissociated automaticity within the isolated PV tissue after successful arteriovenous conduction block (Figure 1). Pacing from each pole of the catheter helps to confirm exit conduction block from the PV if dissociated activity is not observed (Figure 2). The CMC and ablation catheters can be placed through 1 transseptal puncture, usually without difficulty. Some operators prefer to make separate transseptal punctures to improve independent maneuverability of the catheters in the left atrium.

Ablation Catheter
There are many choices for commercially available tip electrode ablation catheters; however, only 1 has been approved for PVI (Thermocool, Biosense Webster, Inc., Diamond Bar, CA).9 There is remarkably little head-to-head comparison data on the safety and efficacy of the various catheter choices, which include 4- to 8-mm tip electrodes without cooling. Power delivery may be limited by high myocardial surface and catheter tip temperatures in areas of low blood flow, particularly regions with trabeculated tissue, where the tip may be surrounded by myocardium. Catheter tips without a cooling mechanism are prone to char formation when tissue coagulates because of excessive surface heating, and smaller lesion size when power delivery is kept low to prevent this unwanted occurrence.10 These problems have been partially overcome by creating ablation catheters with tips that are cooled by external or internal saline irrigation. In a comparison in which a canine thigh muscle preparation was used, an externally irrigated catheter was shown to reduce the potential for thrombus formation compared with an internally irrigated catheter at a constant power output.11 No comparisons have been made in beating heart experiments or during procedures in humans. The obvious disadvantage of an open irrigated catheter is that additional fluid volume (often 2 to 3 L of normal saline) is delivered to the patient, which can require intravenous diuretics to prevent symptoms of congestive heart failure after the procedure.

Intracardiac Echocardiography
Two widely available forms of intracardiac echocardiography are used in the electrophysiology laboratory. Rotational echocardiography is provided on a nondeflectable catheter. It
is excellent for viewing structures in the right atrium and interatrial septum, but requires placement in the left atrium to view the anatomic detail of the PVs, left atrial appendage, posterior wall of the left atrium, and location of the esophagus. Phased-array echocardiography is engineered on a shaft that deflects in 4 planes. It has a larger field of view, and therefore details of the left atrium and esophagus can be seen from the right atrium or ventricle. Anatomic detail can be visualized with intracardiac echocardiography and displayed on an electroanatomic mapping system in 3 dimensions. Although not proven by clinical studies, intracardiac echocardiography probably lowers the risk of complications related to transseptal puncture, particularly with inexperienced operators who are on a steeper portion of the learning curve. In addition, intracardiac echocardiography may make the PVI procedure safer by providing continuous monitoring for pericardial effusion or intracardiac thrombus and is helpful to visualize the position of the esophagus relative to ablation catheter tip position on the posterior wall of the left atrium.\textsuperscript{12,13}

**Key Portions of the Procedure**

**Arrhythmia Induction**

For patients with a history of paroxysmal AF who present for the procedure in sinus rhythm (SR), we generally perform transseptal puncture(s) and PVI before arrhythmia induction is attempted because most operators find interpretation of electrograms to be less ambiguous during SR. Once PVI has been achieved, programmed atrial stimulation including burst atrial pacing and high doses of isoproterenol (up to 20 \(\mu\)g/min) are administered to look for non-PV triggers. For patients who present to the electrophysiology laboratory in AF, we generally perform PVI during the arrhythmia. Rarely
do patients with a history of paroxysmal AF require electric cardioversion to restore SR. Most patients will convert to SR after circumferential PVI; however, if AF persists or is induced and sustained for >10 minutes, we generally map and ablate complex fractionated activity to terminate the AF episode.

**Anticoagulation**
Unfractionated heparin is administered to maintain an activated clotting time goal between 350 and 400 seconds. A 10-mg/kg dose is administered either before or just after the transseptal puncture, or a 6- to 8-mg/kg dose is administered if the INR is 2.0 to 3.5. Some operators prefer administering heparin before transseptal puncture to avoid clot formation on transseptal sheaths and exchange wires placed in the right atrium, which might be inadvertently pulled into the left atrium by placement of catheters through the sheath containing a thrombus. Patients with a therapeutic INR also require fewer repeat boluses to maintain activated clotting time values within the desired range. In addition, constant flushing of sheaths with heparinized saline with incorporation of air filters in the line is critical to preventing thromboembolism or air embolism.

**Transseptal Puncture**
For many inexperienced operators, this is the most feared obstacle to success in performing a successful PVI. The success and safety of transseptal puncture are not dependent on specific equipment or techniques, of which there are many safe ones, but rest largely on the experience of the operator. One method is shown in the linked video. Regardless of the method used, operators should receive extensive training before attempting unsupervised transseptal puncture. Intracardiac echocardiography greatly enhances training, mainly by boosting the operator’s confidence that he or she is going to perforate the septum within the fossa ovalis and that the transseptal needle is pointed away from critical structures such as the aortic root, left atrial appendage, and portions of the posterior wall of the left atrium in close proximity to the septum.

**Titration of Radiofrequency Energy**
Using an externally irrigated ablation catheter with a 3.5-mm tip electrode (Lasso Variable CMC, Biosense Webster Inc., Diamond Bar, CA), we use a power-controlled mode with a temperature ceiling of 50°C, which, when reached, will cause abrupt termination of radiofrequency delivery. We generally suggest no more than 30 W for the relatively thin posterior wall of the left atrium, which may reduce the chances of steam pop formation and perforation and lessen potential damage to the esophagus. In other areas of the left atrium, we will increase energy output up to 40 W as long as the temperature remains below 42°C. Energy is titrated for individual lesions to reduce the amplitude of the electrogram to <0.15 mV if possible, and, more recently, we render the PV antrum nonpaceable at an output of 10 mA/2.0 ms. Depending on the site, 15 to 120 seconds of radiofrequency delivery may be necessary to achieve sufficient lack of excitability.

**Monitoring for Potential Esophageal Injury**
Although rare, one of the worst complications of PVI is atrioesophageal fistula, which is frequently disabling or fatal. Asymptomatic esophageal injury has been demonstrated in 10% to 30% of patients after PVI. Several different techniques are used to avoid potential esophageal damage, including endoluminal esophageal temperature monitoring, visualization of the esophagus with the use of barium swallow, echocardiography, preprocedural imaging, and minimization of energy delivery in proximity to the esophagus. No method is foolproof, and each has its advantages and disadvantages. Barium swallow requires the patient to be awake and creates the potential for aspiration, although the mixture is inert and aspiration has not been demonstrated to occur with great frequency after 5 mL of barium paste is swallowed. Intracardiac echocardiography can be used to visualize the esophagus relative to the tip of the ablation catheter on the posterior wall of the left atrium. Swallowing a small amount of carbonated beverage may enhance the appearance of the esophageal lumen on echocardiogram. Temperature monitors mounted on a catheter can be swallowed, which is less well tolerated in an awake patient, particularly because manipulation of the thermistor to the level of the ablation is necessary. In addition, it is difficult to control the position of commercially available temperature probes relative to the wall of the esophagus. Although a sudden temperature rise (>0.2°C has been suggested as a cutoff by some investigators) certainly indicates direct heating of the esophagus, the frequency of temperature rise may be misleading if the temperature probe is not adjacent to the anterior wall of the esophagus adjacent to the lesion on the posterior wall of the left atrium. Other potential “esophageal protection devices” are in development.

**Other Potential Procedural Complications**
A partial list of complications is included in the Table. Major complications are expected to occur with a frequency of 4.5%. Of course, the frequency of complications varies depending on the experience and skill of the operator. Electrophysiology laboratories performing PVI should have adequate facilities and personnel to deal with sudden emergencies, including a stroke team with quick access to brain imaging and neurointerventional laboratories, cardiac sur-

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<th>Table. Potential Complications of Left Atrial Ablation for AF</th>
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<td>Cardiac tamponade</td>
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<td>Peripheral vascular complications</td>
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<td>Phrenic nerve injury</td>
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<td>Acute coronary occlusion</td>
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<td>Atrioventricular block</td>
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geons on site with a clear plan to deal quickly with surgical emergencies, and interventional cardiologists who can perform coronary angioplasty. Appropriate emergency equipment should be readily available, such as pericardiocentesis trays and cardiac surgical equipment to perform sternotomy in the electrophysiology laboratory if necessary. These complications are rare, but emergency plans should not be developed during an emergency. As an example, cardiac tamponade is likely to occur during a PVI procedure at least once in every busy operator’s career. If the operator is poorly prepared and poorly trained to perform pericardiocentesis (or cannot receive immediate assistance), then the unnecessary delay in draining blood from the pericardial sac may prove fatal.

Postprocedural Care
Catheters are removed after administration of protamine 30 to 40 mg IV and manual pressure applied for at least 10 minutes to venipuncture sites. If the patient has received sufficient fluid volume, bladder drainage may be necessary if a urinary catheter was not placed at the beginning of the procedure. Some patients may require intravenous diuretics to prevent systemic and pulmonary congestion, particularly older patients with a history of diastolic cardiac dysfunction. Four to 6 hours after the procedure, patients who have an INR <2.0 will receive enoxaparin 0.5 to 1 mg/kg twice daily until the INR becomes therapeutic. Although a 1-mg/kg dose of enoxaparin is theoretically desirable to prevent intracardiac clot formation, the risk of significant bleeding complications such as groin hematoma may be increased at this dose, particularly as the INR climbs close to or within the therapeutic range.20 Hence, some operators prefer enoxaparin injection at a dose of 0.5 mg/kg twice daily. Although the AF consensus document supports continuous anticoagulation after the procedure, alternative strategies have not been tested or compared.21

On the basis of animal studies that suggest that atrioesophageal fistula requires not only initial thermal damage to the esophagus but also the presence of gastroesophageal reflux and esophagitis, we give all of our patients proton pump inhibitors immediately after the procedure for a period of 6 to 8 weeks. Unfortunately, this dreaded complication has occurred in patients taking proton pump inhibitors after the procedure.22

Usually within the first few months after catheter ablation, paroxysmal AF episodes may occur with an even greater frequency and duration in some patients, presumably because of the proarrhythmic nature of inflamed and healing lesions in the left atrium. For this reason, patients will usually continue to take an antiarrhythmic medication after the procedure, usually the last antiarrhythmic drug that the patient has been prescribed, for the convenience of the patient. It may be necessary, however, to change antiarrhythmic medication or increase dosages if arrhythmia remains uncontrolled. Warfarin is continued for a minimum of 2 to 3 months after the procedure, as recommended in the AF consensus document.21 Expected success rates range from 60% to 90%, although reported success rates reflect the different techniques, experience level, and monitoring methods of investigators.9,19,21

Summary
In summary, PVI is an effective means to control paroxysmal AF in patients with recurrent, drug-refractory symptoms. With appropriate training and experience, one can expect ~70% of patients to remain free of AF episodes and antiarrhythmic drugs after a single procedure during a 1-year follow-up period.

Disclosures
G. Michaud has received honoraria from St Jude Medical, Medtronic, and Boston Scientific. He has also received consulting fees and research support from St Jude Medical. R. John has received honoraria and consulting fees from St Jude Medical and research support from Rythmia Medical and EP limited.

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Percutaneous Pulmonary Vein Isolation for Atrial Fibrillation Ablation
Gregory F. Michaud and Roy John

Circulation. 2011;123:e596-e601
doi: 10.1161/CIRCULATIONAHA.110.990028

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