New Technologies in Atrial Fibrillation Ablation

J. David Burkhardt, MD; Andrea Natale, MD

The treatment of atrial fibrillation has changed greatly in the past decade. Not long ago, the scientific community argued the benefits of a rate-control strategy versus a rhythm-control strategy. This argument was always hampered by the relative ineffectiveness of the antiarrhythmic medications used as rhythm-control agents. Ablation therapy for the treatment of atrial fibrillation has quickly evolved. Originally, ablation was focused on finding triggers of atrial fibrillation in the pulmonary veins. Now, ablation offers a potential curative strategy for patients with paroxysmal, persistent, or permanent atrial fibrillation. Recent data continue to show that atrial fibrillation ablation is superior to the currently available antiarrhythmic medications in the maintenance of sinus rhythm, and the Food and Drug Administration has approved devices labeled for the ablation of atrial fibrillation.

It is estimated that >2 million people in the United States have atrial fibrillation. Although the number of atrial fibrillation ablations continues to increase year after year, offering this therapy to all potential candidates is impossible because of several limitations. A finite number of fellows are being trained in programs that offer a great deal of experience in atrial fibrillation ablation, and there is limited opportunity for practicing electrophysiologists to learn new techniques. Unlike supraventricular tachycardia ablation, atrial fibrillation ablation requires greater technical skill, significantly more lesions, and time. Like many other medical procedures, technological innovation is likely to be a contributing factor in making atrial fibrillation ablation a more commonplace and widely practiced therapy.

Navigating the complex anatomy of the left atrium is also difficult to master. Imaging technologies have been used to orient the operator to the anatomy and the location of the ablation catheters in this anatomy. With fluoroscopy alone, it is difficult to determine anterior versus posterior orientation or the presence of the catheter in a pulmonary vein versus the left atrial appendage. Intracardiac echocardiography (ICE) provides 2-dimensional navigation assistance and excellent anatomic detail; however, it is difficult to locate the catheter tip at all times in the echocardiography field. Without 3-dimensional (3D) imaging, navigation with ICE alone is also difficult. Electroanatomic mapping (EAM) systems offer a 3D view and nearly real-time catheter tip localization within a created construct of the left atrium, but the data are heavily dependent on the input of the operator and cartographer. Newer technology has merged these 2 imaging modalities to offer the best of both worlds.

Remotely obtained computed tomography (CT) imaging of the left atrium has been performed to define the complex anatomy of the left atrium. This can be integrated into EAMs or imaging systems to aid in navigation and procedure planning. However, conditions at the time of CT may be different from those at the time of ablation. New fluoroscopic systems allow the performance of rotational angiography, which can be used to re-create CT-like images of the left atrium for use in the procedure at the same time.

Two of the current limitations of atrial fibrillation ablation include the use of catheters designed for pinpoint lesions to perform large-area ablations in a point-by-point fashion and the dexterity required to perform such a lesion set. New technologies are aimed at overcoming these limitations. Balloon-based ablation systems and multielectrode ablation catheters attempt to minimize the time to perform the pulmonary vein isolation portion of the procedure, whereas remote ablation technologies attempt to obviate the need for manual dexterity and to automate the ablation procedure.

Imaging Technologies

Three-dimensional EAM systems are frequently used in conjunction with complex ablation. These systems allow the operator to view the catheter location in 3 dimensions within a geometry that is obtained during the procedure by contacting the walls of that chamber. This helps aid navigation and orient the operator to locations and anatomies that are not as easily perceptible by 2-dimensional fluoroscopy. Because catheter tip localization is nearly real time, navigation can be performed with these systems alone. This may help reduce fluoroscopy exposure to the patient and operator. In addition, the acquisition of ablation points helps determine which areas have not been ablated or whether lines are incomplete. The mapping system serves as memory for electric timing in procedures in which activation mapping is performed.

ICE is also frequently used during atrial fibrillation ablation procedures. ICE helps facilitate the transseptal puncture by confirming the position of the needle when tenting of the septum is visualized. Bubbles can be seen in the left atrium after puncture by injection of contrast or saline through the needle, confirming that the needle tip is in the left atrium.
before a sheath is placed. ICE can be used to determine the location of the ostia of the pulmonary veins without contrast injection. Doppler imaging can detect the presence of pulmonary vein stenosis or atrial septal defects. Other critical structures such as the left atrial appendage, esophagus, and aorta can be visualized. During the procedure, ICE may be used to monitor for complications like thrombi on the transseptal sheaths, pericardial effusion, or tissue overheating by microbubble formation. One of the major advantages of ICE is the fact that it is real-time imaging that gives very detailed anatomic information. EAMs may need updating if the anatomy has changed or the location reference has moved. Fluoroscopy is real time, but it does not provide the depth of information that can be obtained with ICE.

One of the limitations of EAM is the lack of real-time anatomic feedback. The geometry may change during the procedure because of volume status or tissue edema during ablation. In addition, some mapping systems require that a catheter physically touch most of the surfaces to obtain the geometry. The major disadvantage of ICE currently is that despite its great anatomic detail, it does not provide memory of surfaces encountered to render volumetric chambers or to provide electric data.

New technology has been able to combine the benefits of both of these technologies. CartoSound ( Biosense Webster, Cincinnati, Ohio) uses a proprietary 3D EAM system and incorporates the information obtained from an intracardiac ultrasound probe into the map. A sensor is present in the ultrasound probe to allow precise 3D localization. Because the location of the tip and the distance of objects seen on the ICE image are known, these data can be added to EAMs. If the ICE image shows the left pulmonary veins in the image plane, this information can be added to the map, or rotation of the probe will allow full geometries to be formed without the use of an ablation catheter in the mapping process. This can result in very rapid generation of complex geometries, particularly compared with the point-by-point method. In addition, because ICE does not require contact with the surface, geometric distortion resulting from distension of the tissue may be eliminated. The ICE probe is also flexible, which allows the operator to collect images from many orientations. If electric information is desired, the ablation catheter can be used to collect it, and this information is applied to the created geometry. The ICE image can be displayed on the EAM to show real-time information and geometry, or the ICE-generated map can be merged with a preacquired CT image (Figure 1). The maps can also be updated frequently to account for changes in volume status or edema. Currently, manual border detection is required to form these geometries, but like transthoracic ultrasound, border detection algorithms are being developed to automate the process. Three-dimensional intracardiac ultrasound probes are being developed. This technology may obviate the need for any geometry. Instead, one could navigate in a real-time 3D image. The mapping system could be relegated to only collecting and storing electric information.

Rotational Angiography
Despite great advances in EAM technologies, x-ray and CT are still used in many electrophysiological procedures. Fluoroscopy is real time but only 2-dimensional. It does not provide great anatomic detail or orientation information. These limitations have helped drive the use of the EAM systems. CT can be used to create 3D reconstructions of the left atrium. They can be imported into x-ray imaging or EAM systems or used before or after the procedure to determine atrial size, number of pulmonary veins, or presence of pulmonary vein stenosis. One of the major benefits of these images is that real patient geometry is obtained. EAMs tend to distort the geometry somewhat because of catheter distention of the cardiac tissue and nonuniform contact, and they depend greatly on the diligence of the operator and cartographer to produce CT-type geometries. For the best maps, many points are required, and careful attention must be paid to angles and structures. CT is able to re-create a real atrium in a short amount of time with great details of veins, appendage, and other vital structures. A major limitation of CT imaging is that it is usually not acquired at the time of the
procedure. Between the time of scanning and the procedure, intravascular volume changes may make the geometry obsolete. The patient may be in atrial fibrillation at 1 point and in sinus rhythm in another. The heart rates may be very different. The esophagus may be mobile and in a different position than at the time of imaging. CT is also not real time; it is a snapshot in time. These limitations prevent CT from being used as a sole navigation aid.

Innovations in imaging technology now allow nearly CT-quality images to be produced from the same fluoroscopy systems in the electrophysiological laboratories. Rotational angiography uses standard fluorescent equipment to obtain several images while rotating around the patient. In the case of atrial fibrillation, contrast is injected into the pulmonary artery or left atrium itself via the transseptal puncture. The c arm is rapidly rotated, and images are acquired throughout the rotation while contrast fills the left atrium. In the case of pulmonary artery injection, a timing bolus is performed to determine how long until the left atrium fills and how long it stays opacified to determine the optimal timing of image acquisition. These images are processed by software to produce 3D CT-quality images that can be used during the same procedure. Because the CT-type image is acquired at the time of the procedure, it may be more likely to represent the true anatomy than a remotely acquired image. Like CT, this image can be viewed or integrated into the imaging system or EAM. Unfortunately, also like CT, iodinated contrast agents and higher-radiation doses are used to generate these images. It also is a snapshot in time. To update the geometry, the image must be fully reacquired.

One of the limitations of rotational angiography has been the speed of rotation. The c arms used for image acquisition are also used in general electrophysiological procedures. Their speed pales compared with that of standard CT scanners. C arms are mounted to a fixed structure, so the table must be mobile to change the field of view, and imaging is usually performed in a single rotational axis. An interesting solution to this problem has been the development of a robotic arm to rotate the c arm rapidly and in nearly any direction. Artis Zeego (Siemens, Medical Erlangen, Germany) uses a car-manufacturing type of robotic arm to manipulate the fluoroscopic c arm. This allows much greater freedom of movement of the c arm and a platform for very rapid rotation. The robotic arm can move up and down the table and in any rotational axis because it is not fixed in space. This improves image quality and makes acquisition much easier. This same system could be used to perform CT-type images of the brain if stroke is suspected or cerebral intervention is needed. It also may be used to evaluate blood vessel–related complications. Future directions could include methods to update geometry or to perform nearly real-time 3D imaging. We hope that imaging with catheters in place could eventually obviate the need for registration of catheters or the requirement to reregister if the patient or reference catheter has moved.

### Ablation Technologies

#### Balloon-Based Ablation Systems

Balloon-based ablation systems are an attractive method of performing pulmonary vein isolation. The balloon system should fit to the pulmonary vein anatomy and offer a method of performing electric isolation with a minimum number of lesions. It is conceivable that pulmonary vein stenosis might be eliminated because the energy could be directed away from the center of the vein. One can see that such a system would be a vast improvement over the pinpoint isolation method and should eventually be faster to perform with less skill required to perform the isolation. The thousands of movements required to isolate all of the pulmonary veins could be replaced by placing a single catheter in each vein and performing a large-area lesion (Figure 3A and 3B).

Balloon-based ablation systems offer the ability to deliver other ablation technologies such as cryoablation, laser, and high-frequency ultrasound. Each of these ablation technologies has different potential benefits. High-frequency ultrasound may offer transmural ablation without the complete occlusion of the vein required with other technologies. Laser therapy can be combined with endoscopic visualization, and cryoablation may have less risk of esophageal injury or ablation-induced perforation.

Balloon-based ablation has had limited success. Pulmonary vein isolation alone does not appear to be adequate for the treatment of persistent or permanent atrial fibrillation. Balloons offer only pulmonary vein isolation and do not address areas such as the posterior wall, septum, roof, mitral valve isthmus, coronary sinus, base of the left atrial appendage, or other areas that may harbor complex fractionated electrograms. These other areas appear to be important for success in ablating nonparoxysmal atrial fibrillation. To address these locations, one would have to use conventional catheters in addition to the balloons. This may not be efficient or cost-effective. Large-area lesions may be needed in areas like the posterior wall, whereas lines or pinpoint lesions may be

![Figure 2. A 3D reconstruction of a left atrium obtained by rotational angiography. LAO indicates left anterior oblique; RAO, right anterior oblique; CRAN, cranial; and CAUD, caudal.](image-url)
needed for the roof, mitral annulus, and areas with fractionated electrograms. Different catheters and possibly different ablation technologies are needed to address these areas. Switching catheters through a sheath may increase the chance of complications and is usually not well accepted by operators.

In addition, although the success rates in paroxysmal atrial fibrillation appear to be reasonable, they appear to lag behind the success rates for standard radiofrequency ablation. Several reasons may explain the differences in success rates. Some operators include some of the non–pulmonary vein locations in their lesions sets, which could improve the success rate. In addition, isolation of the right inferior pulmonary vein is difficult with these ablation systems. The balloon catheters tend to be more inflexible than standard catheters. To reach the right inferior pulmonary vein, a sheath must be used that can orient toward the vein. This can be difficult if the transseptal puncture is too superior or anterior. Because venous occlusion is required with the laser and cryoablation balloons, the sheath must allow enough forward pressure to be applied to occlude the vein. In some cases, isolation of all of the pulmonary veins is not possible. There is significant variability in pulmonary vein anatomy; veins vary in size, location, and number and in location of side branches. These systems may not be able to isolate all anatomic variations, or different balloon sizes or shapes could be necessary to address the differing anatomies. This would certainly add to the cost and complexity of the procedure. Although the hope is that a single application could isolate a pulmonary vein, in reality, several applications are usually needed to create electric isolation with all the systems. The level of isolation with balloons also appears to be more distal than with most ablation techniques. The inability to address the structures in the proximal antrum may explain some of the differences in success rates. In addition, cryoablation therapy may not be as durable as radiofrequency, as was seen in some studies of supraventricular tachycardia ablation. At this point, balloon-based ablation systems have not been proven to be as effective as current techniques and do not appear to save procedure time.

Figure 3. A, Fluoroscopic image of an ablation balloon inflated in the left superior pulmonary vein. The balloon and circular mapping catheter are noted. B, Intracardiac recordings obtained from a pulmonary vein with the circular catheter before ablation. C, Intracardiac recordings obtained from the circular catheter after balloon-based ablation. Complete loss of pulmonary vein potentials is seen.
Complications of balloon-based ablation systems appear to be similar to those of standard ablation. The major difference seems to be that the larger transseptal puncture may be associated with more left atrial access–related complications. In addition, because the ablations appear to be more distal, the incidence of phrenic nerve injury appears to be more frequent.\(^4\) As the system designs are improved and more experience is gained, the safety record may improve.

### Multielectrode Ablation Catheters

Another method of performing large-area ablations for pulmonary vein isolation is using multielectrode radiofrequency ablation catheters. The catheters used for pulmonary vein isolation are circular and mesh array shaped. Other configurations are being used for ablation along the septum, left atrial body, and other locations. Most of the catheters use forms of radiofrequency ablation, including unipolar, bipolar, and pulsed radiofrequency energy, but 1 catheter uses cryoablation. None of the current catheters offer internal or external irrigation. The concept of these catheters is very intriguing. A circular catheter can be maneuvered throughout the left and right atria. Ablation at specific poles could allow pinpoint-type ablation without the requirement for large-area lesions. Currently, these catheters do not appear to be as maneuverable as the circular mapping catheters, limiting their use outside the pulmonary veins.\(^4\)

The early success rates with short follow-up reported with the circular radiofrequency ablation catheter appear similar to those of manual ablation in patients with paroxysmal atrial fibrillation. Operators are able to isolate most veins with this configuration; however, like balloons, several applications are required for each vein. Contact is another important factor in achieving isolation, but rotation of the catheter seems to make up for lack of contact in 1 orientation. Studies have shown the ability to isolate all veins and report 83% success at 6 month follow-up.\(^4\) With the mesh system and cryoablation systems, it has been reported that isolation of all veins is more difficult.\(^5\)\(^6\) As with balloons, isolation of the pulmonary veins does not appear to be adequate treatment for persistent or permanent atrial fibrillation, and success rates appear to be unacceptable in these populations. The other catheter configurations may address this issue, but exchanging catheters during a single procedure is required, which may increase the expense of the procedure, increase complications, and reduce its desirability compared with standard ablation. All of these catheters do not address areas that may not be accessible to large catheters such as the coronary sinus. A trial using a multielectrode radiofrequency ablation system in permanent atrial fibrillation is ongoing.

Other than the potential need for multiple catheters, the main limitation appears to be the lack of available irrigation platforms with the radiofrequency ablation catheters. Most radiofrequency energy ablation of atrial fibrillation performed today uses open irrigation to cool the catheter tip, which allows more energy to be delivered without the limitation of overheating the catheter tip. Despite this limitation, preliminary reports have shown low complication rates. If a large-area ablation system were developed that could perform pulmonary vein isolation, ablation of the posterior wall, and selective right and left atrial ablation through specific poles, it may become the preferred method of atrial fibrillation ablation.

### Force-Sensing Technologies

A recently developed technology may improve the way that current catheters are used. It has been discovered that the force applied to the tissue during radiofrequency ablation dramatically affects the size and safety of the lesion. Too little force results in lesions that are smaller in volume and depth. These lesions may not be effective. Excess force more frequently results in pressure- and overheating-related complications such as steam pops, coagulum formation, or carbonization at the electrode. Such complications may lead to perforation or stroke.\(^5\)\(^1\)\(^2\)

It is difficult for an operator to accurately determine the force at the catheter tip. Sensory feedback, fluoroscopy, and unipolar injury current have proved unreliable. New force-sensing technologies have been developed to aid the operator in applying appropriate force to deliver optimal lesions without risking pressure-related complications. These sensors are able to give instantaneous feedback on the force applied at the catheter tip. The angle of the catheter in relation to the tissue may also be displayed (Figure 4). Early data have shown that this information may reduce these pressure-related complications. More study is needed to determine whether this information results in improved success rates.\(^5\)\(^3\)\(^5\)\(^4\)

### Navigation Technologies

Another method of tackling the challenge of the dexterity required for atrial fibrillation ablation is remote navigation. Instead of designing new catheters, remote navigation technologies use standard ablation catheter technologies and deliver them in a unique way. Instead of controlling the catheter tip from a combination of plunger movements, rotation, and advancing and retracting from 3 feet away, these technologies use instinctive movement and direct interaction with an EAM system. The 2 currently available technologies
include remote robotic navigation and remote magnetic navigation.

Remote robotic navigation uses specially designed steel sheaths that have multiple pull wires. These sheaths are connected to a robotic arm that advances, withdraws, and rotates the sheath and manipulates the pull wires to flex the sheath in 3D space (Figure 5A through 5C). This is controlled by an intuitive user interface that can be synchronized to fluoroscopy, intracardiac echocardiography, or a 3D mapping system. With this interface, movements of the catheter are simplified. Moving the joystick up moves the sheath up on whatever is being used as synchronization. So, if an EAM system is being used in the posterior-anterior view, moving the joystick to the right moves toward the right of the patient, and in an anterior-posterior view, moving the joystick to the right moves the sheath toward the left of the patient. Navigation in the left atrium is relatively easy and intuitive in most cases.55,56 Rarely, a patient’s anatomy does not allow the outer mechanical sheath to sit well on the septum. This results in movement much like a manual catheter with a sheath that has fallen to the right atrium. Because there is no torque point in the right atrium, navigation can be more difficult in this chamber.

Currently, the sheath requires a 14F introducing sheath, usually placed in the left femoral vein. One of the advantages of the technology is that any catheter that can fit through the inner steel sheath can be manipulated or used for ablation; however, the catheter size limitation is between 8F and 8.5F, so larger catheters cannot be used with this system. The steel sheaths are significantly stiffer than manual catheters or standard transseptal sheaths. This allows greater contact with the wall during the cardiac cycle but can generate higher contact forces, which may increase complications or distort maps.52 The system is equipped with a force-sensing technology, but it appears to be limited when the catheter is not perpendicular to the tissue.

The initial experience with the system in atrial fibrillation ablation shows favorable success rates; however, complications were relatively high compared with manual ablation. The majority of complications were related to vascular access and insertion. Because of the large size of the introducing sheath, stiffness of the mechanical sheath, and variable tortuosity of the left femoral vein, more hematomas and bleeding complications were seen. The majority of these complications appear to be reduced by the use of longer introducing sheaths and selection of appropriate patients. In addition, cardiac perforation and cardiac tamponade appeared to be higher during the initial use. Reducing the power and time of ablation in a single location appears to reduce the incidence of this complication.51 Recent studies have shown that success rates can mirror manual ablation in paroxysmal and persistent atrial fibrillation patients with low complication rates. In 1 study that included 29 patients with paroxysmal atrial fibrillation and 11 with persistent atrial fibrillation, 86% were free of atrial fibrillation at the 1-year follow-up while off antiarrhythmic medications. Most of the remaining patients were free of AF while on antiarrhythmic medications. Only 1 cardiac tamponade related to the robotic system was reported in this study. Radiation exposure to the operator was significantly reduced.57

Remote magnetic navigation uses standard ablation–type catheters with the pull wires removed and magnets added to the distal section. These catheters are manipulated in a magnetic field produced by 2 large composite rare earth magnets in a housing on the sides of the patient. These composite magnets tilt, rotate, advance, and retract to change the combined magnetic field vector. An appropriately enabled magnetic catheter can be manipulated in any direction with this vector. A remote catheter advancing and retracting system allows forward and backward movements of the catheter. The magnetic vectors are controlled by a user interface that integrates with a 3D EAM system. The vectors can be changed relative to fluoroscopy, imported images such as CT or magnetic resonance imaging, or generalized directions in the x,y,z axis or based on idealized anatomic models (Figure 6A and 6B). Automated features, including automated mapping, localization, geometry creation, and ablation, can be used with the EAM system. Automation schemes work reasonably well in the smooth surface of the left atrium but are less reliable in more trabeculated surfaces.

Because the catheter tip is being controlled in the magnetic field and the catheters are very floppy in nature, the system can navigate tortuous anatomy. In addition, the catheter does not require sheaths for a pivot point or support. Standard sheaths can be used if desired. Navigation is easy but not as intuitive as robotic navigation. Unlike the robotic system, navigation is similarly easy in all cardiac chambers. The magnetic field strength is a fraction of the strength of standard magnetic resonance imaging systems. The forces produced on
the endocardial surface of the heart tend to be about 10 g to 15 g, which is lower than the average for manual ablation and significantly lower than for robotic ablation; however, the catheter appears to stay in contact with the wall and has less variation in contact forces. This appears to create deeper and larger-volume lesions at comparable forces, and higher forces are required with manual catheters to create similar lesions. In addition, steam pops and perforation are more often related to high contact forces, which are seen infrequently with the clinical use of these catheters (K.H. Kuck, MD, personal communication, 2008). Unfortunately, this constant contact appears to increase the incidence of char formation. It is suggested that the variable contact of manual catheters may help wash the tip during ablation.

An irrigated magnetic catheter has recently been approved in the United States. One limitation of the system is that it relies on available magnetic catheter technology and cannot be immediately adapted to new ablation technologies.

The initial experience of the system in atrial fibrillation ablation has been mixed. Most of these data are based on 4-mm solid-tip catheters, not the current state-of-the-art irrigated-tip catheters. Pappone et al.\(^58\) reported very high success rates in achieving venous isolation based on electrogram reduction; however, Di Biase et al.\(^59\) reported a very low incidence of isolation based on circular catheter–based electric isolation and subsequently a very low success rate. Char formation was also seen in one third of the cases. Despite the low success rate and char formation with the solid-tip catheter, the authors reported enthusiasm about remote magnetic navigation. Katsiyiannis et al.\(^60\) reported an 80% success rate with a 1-year follow-up in 20 patients who underwent ablation with the 4-mm solid-tip catheter.

Nearly all authors have reported an excellent safety record with the system. As stated, the lower contact forces may reduce pressure-related complications, including steam pops and perforations. The standard catheter sizes and lack of need to rotate the catheter from the distal end may reduce the groin-related complications. The safety profile of the system has been quite remarkable compared with manual or other technologies. A reduction in radiation exposure for the operator and the patient has also been nearly universally reported.\(^59\)–\(^62\) The close interaction with the EAM system is likely the main reason for the reduction in fluoroscopy. These navigation technologies hold great promise but require adaptation to the newer ablation technologies for long-term survival.

**Conclusions**

Atrial fibrillation ablation is fast becoming the preferred treatment of symptomatic atrial fibrillation. Some studies have even suggested that it may be a first-line approach in a
very select population.63,64 The superiority of ablation over antiarrhythmic medications makes it a more reasonable com-
parative strategy when studying rate versus rhythm control.62
If atrial fibrillation ablation becomes the preferred treatment strategy, then technological innovation will be required to make it a procedure that can be readily performed by many individuals in a short period of time with high success rates and low complication rates. Technologies such as multi-
image integration with mapping systems, rotational angiogra-
phy, balloon-based ablation systems, multielectrode abla-
tion systems, and remote magnetic and robotic navigation systems are being developed to address many of the limita-
tions preventing this procedure from being more common-
place. With the expected increase in the prevalence of atrial fibrillation and expanding indications for ablation, these technologies are welcome additions to the current tools in delivering optimal therapies to these patients.

Disclosures
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