Catheter ablation of atrial fibrillation (AF) has been demonstrated an effective treatment option for symptomatic AF. The most commonly performed procedure within the broad category of AF ablation is pulmonary vein isolation (PVI). Its role in controlling AF has remained central to that of all AF procedures and is essential to AF control because it abolishes the most common source of AF triggers.\(^1\) Although freedom from AF can be achieved with this procedure alone, AF ablation currently remains imperfect with suboptimal success rates.\(^2\) The limitations currently experienced in AF control via ablation stem from shortcomings of current ablation technologies in their ability to create safe and reliably permanent lesions. In addition, in more chronic forms of AF, there exists an incomplete understanding of the mechanisms maintaining AF that can be used to identify specific targets for ablation. This review discusses recent technological advances in AF mapping as well as in catheter ablation.

Broadly, novel approaches to catheter ablation for AF (paroxysmal as well as persistent) can be grouped based on the particular aspect of AF that the technology specifically aims to improve: one novel approaches within mapping systems and another novel approaches to atrial ablation.

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NOVEL APPROACHES WITHIN MAPPING SYSTEMS

Currently used electroanatomic mapping systems include systems that are commonly referred to by the name of their marketed mapping platforms. These include 3 major systems—CARTO ( Biosense Webster, Irvine, California), EnSite NavX (St. Jude Medical, St. Paul, Minnesota), and Rhythmia (Boston Scientific, Natick, Massachusetts). Electroanatomic systems use magnetic and impedance information to localize catheters in 3-D space without use of ionizing radiation. Several commercial versions exist within each of these systems and, when looked at broadly, they are primarily designed to provide information on atrial anatomy and tissue voltage. In addition to rendering anatomy in real time, previously acquired CT or MRIs may be integrated into the map, allowing for increased anatomic accuracy, although mapping-based rendering of anatomy has improved to the point that imaging is no longer critical. These maps provide a topographically accurate path for an operator to move the ablation catheter (also visualized within this 3-D map) along the desired areas of the atria. Current systems have automated algorithms that place tags along this path providing not only a road map but also a historical record of all ablations performed. Electroanatomic mapping thus can now be used to assess contiguity of lesions in an accurate manner (Fig. 1).

Novel approaches within the systems that either have the potential or have been proven of significant value in improving AF ablation outcomes are briefly highlighted.

High-density Mapping

The occurrence of recurrent atrial tachycardias (ATs), both focal and macroreentrant, after PVI is not uncommon and is often an unavoidable outcome of ablation strategies used for chronic forms of AF. These ATs can be mapped and successfully eliminated and, therefore, are to long-term arrhythmia-free status of AF ablation patients. High-density mapping refers to the process of mapping of electrical activity through the rapid acquisition of a high number of points that are acquired with catheter with multiple closely spaced electrodes. All major mapping systems offer this feature with system-to-system differences. This technique has transformed the way atypical flutters are approached, in that the automated mapping modules within these systems allow for rapid characterization of complex circuits. High-density maps often helps an operator identify critical sites that sustain the AT, which when ablated often result in durable control of the arrhythmia (Fig. 2). Investigators have demonstrated that by using novel ultra–high-density maps, detection of gaps within incomplete PVI lesions sets is improved compared with using traditional high-density maps.

Atrial Fibrillation Mapping Systems

AF mapping approaches are primarily designed to treat persistent AF, where the role of extra–pulmonary vein (PV) substrate is considered to be significant as PV isolation by itself has been shown to be insufficient for AF control. The systems that are commercially available and those under

Fig. 1. Electroanatomic rendering of left atrial anatomy (left) compared with segmented CT scan of the left atrium (right) (A). Automated tagging of lesions depicting wide area circumferential PV isolation (B).
development have been specifically designed to identify sites that are believed critical to maintenance AF. AF mapping systems aim to identify putative drivers of AF, which include focal impulses and reentrant spiral waves (rotors) and thereby offer specific targets for ablation that can improve AF control beyond PVI alone. Spectral analysis is used to localize areas with the highest activation frequencies, which coincide with location of AF foci or rotors. Phase mapping determines the local phase of the activation/recovery cycle at each time point, which enables visualization of spatiotemporally distributed patterns of propagation. The 2 most widely used systems are the focal impulse and rotor modulation system (FIRM) (Abbott, Minneapolis, Minnesota) and the noninvasive panoramic mapping system (CardioInsight, Medtronic, Minneapolis, Minnesota). In addition there are newer mapping systems that use different approaches to AF mapping that are being investigated (Fig. 3).

**Focal Impulse and Rotor Modulation System**

The FIRM system uses a 64-electrode basket catheter to identify rotational drivers by recording simultaneous intracardiac electrograms in the atrium and uses phase-mapping algorithms to identify focal impulses and rotors. These areas are then ablated with the standard ablation catheter of the operator’s choice. Early studies reported widely disparate findings, which has resulted in controversy over its efficacy. The CONFIRM (Conventional Ablation for AF With or Without Focal Impulse and Rotor Modulation) trial included 92 patients with paroxysmal AF or persistent AF and randomized them in a 1:2 fashion to FIRM-guided ablation followed by conventional ablation or conventional ablation alone. The investigators found FIRM-guided ablation had a significantly higher freedom from AF with a single procedure (82.4% vs 44.9%; \( P < .001 \)). At 3 years’ follow-up, patients receiving FIRM-guided ablation were found to have high rates of freedom from AF (77.8% vs 38.5%; \( P = .001 \)). In the OASIS (Outcome of Different Ablation Strategies in Persistent and Long-Standing Persistent Atrial Fibrillation) trial, which prospectively evaluating FIRM ablation versus PVI and FIRM versus PVI, posterior wall, and non-PV trigger ablation in nonparoxysmal AF, investigators found that FIRM-guided ablation was inferior at 1 year with regard to freedom from AF (14% vs 52.4% vs 76%, respectively) and that procedures using FIRM were significantly longer. More recently a meta-analysis of 17 studies and 3294 patients using FIRM showed a statistically significant improved odds ratio for freedom from AF with the addition of rotor mapping and ablation. The addition of driver ablation resulted in freedom
from AF at 72.5% and from all arrhythmias at 57.8%; when driver ablation was added on to PVI compared with control, the odds ratio of freedom from AF was 3.1 (CI, 1.3–7.7; P = .02) and freedom from all arrhythmias of 1.8 (CI, 1.2–2.7; P < .01).8 Due to the conflicting results of studies demonstrating utility of FIRM-based ablation of persistent AF, this approach has not gained widespread acceptance. Additional clinical studies, such as the REAFFIRM and REDO-FIRM clinical trials, are ongoing to provide greater clarity to the effectiveness and clinical utility of this technology.

Noninvasive Panoramic Mapping

The noninvasive panoramic mapping (CardioNXT, Medtronic) system uses ECGi, a noninvasive technique based on phase analysis of body surface potentials, with a 252-electrode vest worn on the torso combined with noncontrast CT to create high-resolution 3-D patient-specific images of epicardial electrical propagation in AF (see Fig. 3). Activation and phase maps are created from unipolar AF electrograms acquired from multiple windows from the vest electrodes during R-R intervals greater than or equal to 1000 ms that are then signal processed to identify drivers. Investigators have reported on 103 consecutive patients with persistent AF who underwent noninvasive mapping to identify drivers. They identified drivers that were ablated in the intervention arm whereas the comparison arm underwent a more traditional ablation approach of stepwise ablation consisting of PVI plus additional ablation. Of the drivers identified, a majority of were reentrant in nature (80.5%), with focal drivers less common (19.5%). Ablation of these drivers terminated AF more commonly in patients with AF of shorter duration. At 12 months, 85% patients with AF termination were free from AF, similar to the control population (87%).10

In addition, studies have demonstrated that the number of rotors found has been shown associated with the extent of late gadolinium enhancement on cardiac MRI, with clustering near scar borders.11 Currently this approach is limited by its inability to accurately map septal locations (that remain hidden when viewing the atria from its epicardial aspect) and/or overlapping structures, its spatial accuracy, and its limited resolution for electrograms less than 0.15 mV.12 Further investigation as well as improving technical aspects are ongoing and its role in persistent AF remains to be established.

Noninvasive Epicardial and Endocardial Electrophysiology System

A noninvasive epicardial and endocardial electrophysiology system (NEEES) has also been used to identify rotors and focal arrhythmias by creating isopotential and phase maps. This system uses up to 224 unipolar ECG electrodes in special arrays fixed onto a patient’s torso, followed by a thoracic MRI performed on the same day. 3-D epicardial and endocardial biatrial geometry is reconstructed with proprietary software (EP Solutions, Yverdon-Bains, Switzerland). In a study of 10 patients with persistent AF examining the relationship between drivers detected with noninvasive panoramic mapping and anatomy, rotors based on NEEES analysis were found not regionally associated with areas of late gadolinium enhancement on MRI in contrast to the study done with the CardioNXT system.13 Further investigation is ongoing at the present time.

Other mapping systems for AF drivers under investigation include a 64-pole basket catheter and offline algorithm to identify reproducible biatrial repetitive activation patterns (CARTOFINDER, Biosense Webster). Early studies have shown this novel technology effective.14 Another driver mapping technology uses a novel computational high-resolution spatiotemporal mapping algorithm to identify focal impulses and rotors from endocardial signals recorded with a multielectrode catheter in persistent AF (CardioNXT, Westminster, Colorado). By synchronizing multiple sequential samples of electrograms with a conventional mapping catheter, a high-density endocardial contact map is generated. These systems are currently being evaluated and results in terms of AF control remain to be determined.

The field of AF mapping technologies has progressed significantly and continues to grow and evolve. Although some clinical studies performed at select centers have demonstrated utility and efficacy to this approach, these experiences have not been consistently replicated by other investigators and further studies as well as improvements in technical aspects of their mapping approaches are needed to fully understand and address their true potential. Finally, these approaches need to be tested in large multicenter randomized studies to fairly assess their impact on AF outcomes in this challenging population.

ALTERNATE APPROACHES

Mapping of triggers outside of the PVs has been shown to be effective. Non-PV triggers have been found both in patients with paroxysmal AF and patients with persistent AF.15 Targeting non-PV triggers after PVI was demonstrated an effective strategy in a prospective study of patients with paroxysmal AF with and without heart failure, with 175 patients in the heart failure arm further
divided by PVI alone (n = 87) or PVI and additional non-PV trigger ablation (n = 88). The investigators found long-term freedom from AF at 15.8 months ± 4.7 months superior in the PVI plus non-PV trigger ablation arm (75.0% vs 32.2%; P < .001) and similar to the group of patients without heart failure (75.0% vs 81.7%; P = .44).16 This study and other studies have brought attention to the concept of adding the search of non-PV triggers as an important step in improving AF control after ablation. Studies of non-PV trigger sources have found the most common sources the left atrial posterior wall, left atrial appendage, ligament of Marshall, superior vena cava, coronary sinus, and crista terminalis. Empiric ablation to isolate these structures is a widely used strategy. The randomized BELIEF trial demonstrated that empiric isolation of the left atrial appendage in long-standing persistent AF can improve long-term freedom from AF and offers another strategy that can help improve AF ablation outcomes in this specific population of AF patients.17 Isolation of the left atrial appendage remains controversial due to concerns about increased risk of thrombus formation. The aMAZE study to evaluate left atrial appendage ligation using the LARIAT (SentreHEART, Redwood city, CA) device at the time of PVI is ongoing to evaluate efficacy and safety of this technique in persistent AF and long-standing persistent AF.

Several other strategies that do not rely on mapping AF drivers/triggers have been developed to increase the success of catheter ablation of chronic AF beyond PV isolation alone. One approach that has been proposed is a substrate-based ablation targeting areas of scar. The presence of low voltage has been shown to predict recurrence after AF recurrence after ablation in paroxysmal AF (36% vs 6%; hazard ratio 5.89).18 Investigators have demonstrated that ablation of sites with distinct activation characteristics within/at border zones of LVA in addition to PVI is more effective than conventional PVI-only strategy for persistent AF.19,20 The ongoing DECAAF II clinical trial is studying conventional PVI versus PVI plus fibrosis-guided ablation, where fibrosis is defined by scar detected by cardiac MRI. Other investigators have proposed using current electroanatomic mapping systems and multielectrode mapping catheters to identify areas of spatiotemporal dispersion and suggest that targeting these areas for ablation can be an effective strategy for AF termination and, therefore, long-term control.21 Finally, any discussion of persistent AF ablation strategies would be incomplete without discussing the role of complex fractionated atrial electrograms (CFAEs) ablation. CFAEs can be identified using automated features of these systems as well as by looking for certain ablation catheter characteristics, and early reports suggested this approach to have utility. More recent reports have shown that when added to standard PV ablation, CFAE ablation failed to improve outcomes in paroxysmal AF and persistent AF patients.22,23 The STAR AF II trial tested PVI alone versus additional CFAE ablation versus additional empiric linear ablation across the left atrial roof and mitral isthmus and found no significant difference in freedom from AF between the 3 strategies at 18 months in patients with persistent AF.24

In summary, new mapping approaches and technologies are based on evolving and improved understanding of AF mechanisms. Although some approaches have become more commonplace, some remain confined to limited centers. Although these technologies show promise, further development of each approach as well as further randomized studies are needed to establish their role in AF management. Until then, pursuing PVI in its most complete and durable form remains a reasonable goal.

NOVEL APPROACHES TO ATRIAL ABLATION

Creation of safe yet consistently transmural atrial ablation lesions is highly desirable not only to achieve durable PVI but also to ensure durable elimination of non-PV targets (triggers and flutter circuits). Reconnection of PVs during redo ablation has been seen in up to 50% of all ablated PVs in early studies.25 In a systematic review of AF ablation outcomes, the primary mechanism for recurrence found at the time of a repeat procedure was electrical reconnection of the PVs.26 These findings were supported by the GAP-AF trial, where investigators assigned patients to complete PVI versus incomplete PVI; 117 patients who had complete PVI underwent an invasive reevaluation of the PV 3 months after their index ablation. AF recurred in 62.2% of patients, and, in the 93 patients who underwent the invasive repeat study, 65 (69.9%) of patients were found to have conduction gaps. Among patients who had been randomized to incomplete PVI, the rate of recurrence at 3 months was significantly higher (79.2%) of patients, illustrating the importance and superiority of complete PVI over incomplete isolation.27 These data reinforce the importance of durable PVI and the need for improvement in existing ablation technology. Modern point-by-point RF ablation and balloon-based ablation techniques are the most commonly used approaches for PV isolation and have yielded improved overall outcomes in recent
years due to advances in catheter technology. They do not, however, reliably create permanent transmural lesions in all patients and have other limitations, such as a distal level of isolation with many balloon-based PV isolation technologies. Moreover, these approaches to ablation are not tissue selective for myocardium, in that they also affect adjacent structures, such as the esophagus and phrenic nerve, in pursuit of creating transmural lesions. Several developments have occurred within these established technologies as well as in novel approaches to ablation that have improved the ability to create transmural ablation lesions with reasonable safety (described later).

Radiofrequency Ablation

Radiofrequency (RF) ablation works by creating resistive heating immediately under the RF catheter tip followed by conductive heating that allows for expansion of the lesion. The size of an ablation lesion is related to the amount of power delivered over time, which in turn is significantly affected by catheter-tissue coupling. Catheter-tissue coupling in turn is determined by the contact force exerted by the catheter tip onto the tissue.28 Several strategies within the realm of RF ablation have been created to improve outcomes.

Contact force and radiofrequency indices

Contact force and RF indices refer to the abilities of catheters to provide feedback about contact to tissue and to assess individual ablation points with respect to various parameters, respectively. Clinical studies have demonstrated that ablation with higher contact force correlated with improved clinical outcomes.29 Contact force–sensing catheters are currently available commercially, and, although these catheters have not been specifically shown to improve outcomes compared with non–force-sensing catheters in large multicenter trials,30 they have become widely accepted as an essential part of initial AF ablation procedure that involves PV isolation. More importantly, the use of these catheters has allowed for the development of lesion/RF indices that incorporate various parameters essential to lesion formation, such as stability, contact force, impedance drops, and duration of ablation (eg, the force time index). Other scores that are more comprehensive include parameters, such as power (lesion size and ablation index). Together these indices have helped standardize RF delivery, and recent data demonstrate that if ablation is performed using these parameters with strict adherence to lesion proximity, AF outcomes and durable PV isolation rates can be improved.31 In the PRAISE study, ablation index–guided ablation was performed in 40 consecutive persistent AF patients with a target ablation index of 550 followed by a protocol-mandated repeat procedure in 2 months. PV reconnection was seen in at the repeat electrophysiology study in 22% of patients, affecting 7% of PVs; at 12 months, 95% of patients were in sinus rhythm, with 10% having started antiarrhythmic drugs.32 The use of this information to track individual ablation points allows operators to manipulate various parameters to reach index targets that correlate to predictable lesions and better outcomes.33 In conclusion, several studies have demonstrated that the use of force-sensing catheters to create lesions that reach specified targets, and using the contact force information in indices can have a positive impact on the outcome of AF procedures compared with traditional RF delivery approaches with the same/similar catheters.

Modulation of irrigation in radiofrequency ablation

Irrigation refers to the saline-mediated active cooling of the RF catheter tip that currently is the standard for all ablation catheters used in AF ablation. This is achieved by delivering saline to the tip surface via a variety of designs specific to the catheter tip. Active irrigation mitigates the risk of char formation by actively cooling the catheter tip and thus allowing greater power to be delivered, which in turn improves lesion depth. A risk of this approach, however, is that lesions can be created with excessive depth on the posterior left atrial wall that could result in esophageal injury. Recently, manipulating the flow rate to avoid creating excessively deep lesions on the thin posterior wall of the left atrium has emerged as a strategy to improve safety and avoid esophageal injury. In a recent study, Kumar and colleagues34 studied lesion characteristics of low-flow ablation in a swine model and evaluated efficacy and safety in a patient cohort. The investigators found that low-flow ablation lesions had a greater diameter at the surface compared with high flow, in which greater diameter was found deeper in the tissue. With regard to safety and efficacy, in a clinical comparison between the 166 patients treated with high-flow irrigation and 160 patients treated with low-flow irrigation, there was no difference in acute PVI, complications, or 12-month arrhythmia-free survival between the treatment groups. Titrating flow at the catheter tip to reduce depth on the posterior wall is a feasible and effective option that may reduce risk of esophageal complications.
**High-power, short-duration radiofrequency strategy**

The strategy of high-power RF applied for very short durations has recently emerged as an approach to maximize lesion dimensions without excessive depth, capturing an essential requirement for ablation of thin-walled atrial tissue. The rationale for this approach is based on the fact that traditional RF ablation lesions (low–moderate powers for longer durations) are created both by resistive heating immediately under the catheter tip and a zone of conductive heating. A high-power burst of RF, on the other hand, results in a larger resistive heating zone, and the short duration results in shorter temperature decay with reduced conductive heating. This prevents the lesion from acquiring unwanted depth with a corresponding reduction in risk of collateral tissue damage. An ex vivo bovine model used to assess lesion characteristics with either increasing power delivery or duration in the setting of fixed contact force found that although both greater power and longer duration of lesions increased size, the proportional increase in power produced significantly larger lesion volume. In a separate in silico simulation study, high-power, short-duration lesions (50 W/13 s, 60 W/10 s, 70 W/7 s, and 80 W/6 s) were compared with standard RF ablations (30 W/30 s) and similar lesion volumes found. High-power, short-duration lesions, however, had significantly larger diameters and smaller depth. A novel ablation catheter (QDOT MICRO, Biosense Webster) that has multiple thermocouples that allow for catheter tip-tissue temperature measurements has been studied in swine to test a higher-power, short-duration strategy against 25-W/20-second lesions. High-power ablation (90 W/4 s) resulted in continuous transmural lesions compared with standard catheter ablation that had linear caps in 25% and partial thickness lesions in 29%. Clinically, the high-power, short-duration technique has been validated in a prospective trial of 51 patients with either paroxysmal AF or persistent AF with 50-W ablation lesion achieving lesion size index of 5.5 to 6 and loss of pace capture as a target for ablation endpoint. The study found single-procedure freedom from paroxysmal AF 86% at 2 years and freedom from persistent AF 72% at 2 years. These approaches are currently being prospectively examined. Although this strategy appears attractive in that it can reduce procedure times, its safety and efficacy compared to traditional approaches remains to be convincingly established.

**Temperature-controlled radiofrequency ablation**

Newer ablation catheters with unique designs have allowed revisiting temperature-controlled ablation strategies by incorporating temperature sensors, described previously, to detect the temperature at the catheter-tissue interface. This approach to RF delivery uses the temperature data acquired despite the presence of saline irrigation to dynamically alter the power delivered so as to optimize RF delivery. One such catheter (DiamondTemp, Advanced Cardiac Therapeutics, Santa Clara, California) is a composite-tip diamond-embedded irrigated RF catheter with 6 insulated thermocouples on the ablation tip (Fig. 4). The diamond rapidly diffuses heat, and the distal electrode can provide electrograms at higher resolution than standard 3.5-mm or 4-

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**Fig. 4.** Temperature-controlled RF ablation demonstrating reduction in catheter tip electrogram (A). Demonstrates the power rising from 25 W to 40 W over the course of this 22-second ablation in a swine experiment (B).
mm ablation catheter electrodes. A preclinical study using this catheter found that ablation performed with a temperature limit of 60°C/50 W resulted in transmurality in 92.7% of atrial lesions. This ablation catheter recently was evaluated in a single-center human feasibility trial for atrial ablation, where RF was delivered in temperature control mode. In this study, 35 patients underwent ablation with the novel catheter and were compared with a cohort of historical patients who had undergone RF ablation using a standard contact force–sensing catheter. PVI was achieved in all patients without any instance of char or thrombus formation. The study cohort had shorter procedures and lower acute dormant PV reconnection rates. At 3 months, at the time of a prespecified remapping procedure done in 23 patients, 84.8% of PV pairs remained durably isolated. This novel technology is currently being evaluated in a multicenter randomized study and further data are needed to understand its true advantages and impact on patient outcomes.

In summary, these and other advances in RF catheter ablation technology have demonstrated improvements in delivery of RF both from safety and efficacy perspectives. This has improved creation of ablation lesions that are tailored to the unique milieu of the atrium. Next-generation ablation catheters that incorporate several of these strategies in a single platform are currently being investigated and offer the prospect of rapid, safe, and durable lesion creation that may have significant impact on procedural workflow, patient safety, and durable outcomes.

**Balloon-based Ablation Catheters**

Balloon-based ablation catheters have become a popular alternative to point-by-point RF ablation in that they can achieve PV isolation rapidly and safely with a 1-shot approach and do not require electroanatomic mapping of the chamber. They have been shown safe and noninferior to traditional point-by-point RF ablation in multiple studies. Several balloon catheter technologies are commercially available or are under investigation (Fig. 5).

**Cryoballoon**

The cryoballoon (Arctic Front Advance Cryoballoon, Medtronic) ablation technique involves occluding PVs individually and decreasing the balloon temperature to freeze tissue and affect tissue necrosis. In the FIRE AND ICE study, cryoballoon ablation was found noninferior to RF ablation in terms of efficacy and had a similar safety profile in a randomized trial of 762 patients with paroxysmal AF; 378 patients were assigned to cryoballoon ablation and 384 patients to the RF ablation arm. At 1.5 years’ follow-up, freedom from AF (34.6% vs 35.9%; \( P \leq .001 \) for noninferiority) and safety was similar (10.2% vs 12.8%; \( P = .24 \)) between both groups.40 The third-generation cryoballoon (Arctic Front Advance-Short Tip, Medtronic) has been designed with a shorter distal tip (8 mm compared with 13 mm) to facilitate more accurate identification of the time to PVI, which is an

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**Fig. 5.** Different balloon catheter ablation systems that are available or in study. Arctic Front Advance™ Cardiac Cryoablation Catheter (A), visually guided laser balloon (B), Satake HotBalloon (C), Apama RF Balloon (D), Kardium Globe (E), and Helios (F) are shown.
indicator of acute and durable PVI. A study comparing the second-generation with the third-generation cryoballoon found similar rates of acute PVI but more frequent recorded time to isolation (89.2% vs 60.2%; \( P < .001 \)), fewer applications (1.6 ± 0.8 vs 1.7 ± 0.8; \( P = .23 \)), shorter left atrial time (43 min ± 5 min vs 53 min ± 16 min; \( P < .001 \)), and shorter procedure time (71 min ± 11 min vs 89 min ± 25 min; \( P < .001 \))."\(^{11}\) More recently, the cryoballoon has been leveraged for isolating the posterior wall, a frequent target for ablation in persistent AF after PVI. Aryana and colleagues\(^{42}\) demonstrated the efficacy of this technique in another study of 390 consecutive patients with persistent AF. Posterior wall isolation with cryoballoon was performed and resulted in greater freedom from AF compared with PVI alone. Adjunct RF ablation was necessary to complete posterior wall isolation in 32.4% of patients. Cryoballoon ablation is widely popular and effective, and refinements to catheter technology and new ways of utilizing the balloon technology have expanded its relevance.

**Laser balloon**

The visually guided laser balloon (HeartLight, CardioFocus, Marlborough, Massachusetts) is a real-time endoscopic system that similarly involves isolating PVs individually. The balloon is compliant and has variable sizes and is inflated with fluid. The balloon is used to occlude the target PV, and 980-nm laser energy is delivered with a maneuverable 30° light arc to ablate tissue. It has been validated in clinical studies for paroxysmal AF\(^{43}\) and persistent AF,\(^{44}\) with efficacy similar to conventional RF ablation. The pivotal multicenter clinical trial randomized 353 patients to ablation with the visually guided laser balloon or conventional RF ablation. The primary efficacy endpoint, which included freedom from recurrent arrhythmia, failure to isolate all PVs, and use of antiarrhythmic drugs, was met in 61.1% of the balloon arm versus 61.7% in controls (\( P = .003 \)), and the safety endpoint was met, although diaphragmatic paralysis was significantly higher in the laser balloon arm.\(^{45}\) Long-term outcomes after laser balloon ablation also have been reported. In a cohort of 90 patients, 5-year freedom rates from arrhythmia recurrence after a single procedure was 51% and 78% respectively with multiple procedures.\(^{46}\) A multicenter remapping study to assess durability of PVI with the laser balloon was performed in 52 patients after 105 days ± 44 days and found 162 of 189 (86%) PVs remained isolated and 32 of 52 (62%) of patients had all PVs isolated. The likelihood of achieving durable PVI differed among operators who performed fewer than 10 procedures versus those who performed more than 10 (73% vs 89%; \( P = .011 \)).\(^{47}\) Laser balloon has demonstrated effective for PVI and, more recently, a third generation laser balloon (HeartLight X3, CardioFocus) has been developed that can create rapid, uninterrupted and continuous lesions and is being currently investigated. Although limited by tissue selectivity, the laser balloon represents an alternative solution to achieving rapid PVI.

**HotBalloon**

The hot balloon ablation system (SATAKE HotBalloon, Toray Industries, Tokyo, Japan) uses thermal energy from a heated compliant balloon to ablate tissue. The balloon is heated with RF energy generated from a coil electrode on the catheter shaft that agitates fluid inside the balloon. In a prospective randomized controlled study of 143 patients with paroxysmal AF, 100 were randomized to the hot balloon and 43 were randomized to antiarrhythmic drug therapy. Acute PVI was achieved in 98% of veins in 93% of patients in the hot balloon arm. At 9 months’ follow-up, chronic success defined as freedom from AF was demonstrated in 59.0% of the hot balloon arm compared with 4.7% of the antiarrhythmic therapy arm. In terms of safety, the rate of major complications was 11.2%, including PV stenosis (5.2%) and phrenic nerve injury (3.7%).\(^{48}\) Subsequent clinical trials have similar efficacy results, although often additional touch-up RF lesions were needed for complete PV isolation.\(^{49}\)
**Novel radiofrequency balloons**

Several novel irrigated balloon-based catheters that deploy RF energy are currently undergoing clinical investigation and appear promising. One such balloon, is an endoscopic balloon catheter system (Apama Radiofrequency Balloon Catheter System, Boston Scientific) that has multipoint RF delivery capabilities that facilitate single-shot PVI as well as potentially linear or focal ablation. Early data from a first-in-man trial, AF-FICIENT, has suggested both safety and efficacy with short procedural times. Another novel irrigated RF balloon catheter (Helios, Biosense Webster) allows for directionally tailored energy delivery for PVI by customizing the amount of energy delivered at chosen locations in an attempt to reduce the risk of collateral injury. Early safety and efficacy for this catheter for PVI was demonstrated in the multicenter RADIANCE feasibility study. Finally, a multielectrode array catheter (Globe Mapping and Ablation System, Kardium, Burnaby, British Columbia, Canada) that has 122 flat electrodes on an expanding, contact-based, semicompliant array has also been developed. This system can create high density activation and voltage maps, is able to pace as well as deploy RF to ablate tissue. An early feasibility study demonstrated efficacy and safety and further studies are ongoing.

**Alternative Energy Sources**

**Irreversible electroporation or pulse electric field ablation**

The novel and investigational energy source, irreversible electroporation, or pulse electric field (PEF) ablation, ablates tissue via a nonthermal mechanism, that is, by creating permanent microscopic pores in cell membranes that result in cell death. This energy source has been used to ablate tumors and has recently been investigated in preclinical models for cardiac ablation. PEF is unique in that it spares the extracellular matrix and has tissue-specific effects, a combination that allows for ablation of targeted myocardium only, with a very low risk for collateral injury, as indicated by preclinical experience so far. There are significant preclinical data supporting the safety of irreversible electroporation/PEF in the context of the esophagus, phrenic nerve, coronary arteries, and PV stenosis (Fig. 6). Recently, first-in-human studies have been undertaken that have demonstrated that PEF-based PV ablation is feasible and safe. This early work was a small single-center study that reported only acute procedural outcomes. Significant work needs to be done in this field and its ultimate role as an ablation therapy remains to be further defined.

**The Role of Esophageal Protection**

Esophageal injury is an uncommon but potentially life-threatening adverse event associated with AF ablation due to the close proximity of the posterior left atrium to the esophagus. The authors strongly believe this is an important area that needs to be considered in the realm of novel ablation technologies that use thermal ablative mechanism. The high mortality rates associated with a particularly extreme form of esophageal injury, the atrioesophageal fistula, should serve as an important reminder of the severe consequences of esophageal injury, and this risk should be constantly and carefully evaluated as new ablation technologies evolve. An atrioesophageal fistula occurs when esophageal tissue is thermally injured and necrosis occurs, eventually ulcerating and forming a connection between the esophageal lumen and left atrium. One of the more common strategies used for esophageal protection is that of monitoring luminal esophageal temperatures during ablation. Several probes are available for this purpose, including single-thermistor and multithermistor probes. The advantage of multithermistor probes with greater sensitivity is earlier detection of temperature elevation. More recently, several strategies of esophageal deviation to prevent injury have been described. These novel technologies prevent esophageal injury by moving the esophagus physically away from the area of ablation.

**SUMMARY**

Catheter ablation technologies for treatment of AF have developed rapidly and along several different lines to fill unmet needs. New ablation technologies including single-shot PVI approaches are designed to enable quicker and durable ablation lesions and will likely lead to improvements in long-term freedom from AF. This as well as their safety remains to be established at this time. Although early results are encouraging, clinical trials are needed to validate these new tools.

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