

Surgical Treatment of Atrial Fibrillation

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ABSTRACT: The surgical treatment of atrial fibrillation (AF) has evolved significantly over the last 20 years and even more so in the last 5 years. There are now many clinically successful surgical procedures focused on eliminating AF and AF-related stroke. This review discusses the current types of surgical AF procedures, including minimally invasive and hybrid, and may assist clinicians in understanding the various surgical AF options available to patients today.

INTRODUCTION

Surgical treatment of atrial fibrillation (AF) can be classified as concomitant, stand-alone, or hybrid surgical AF ablation procedures or as isolated left atrial appendage (LAA) closure to eliminate AF-related stroke risk. A concomitant surgical AF ablation procedure is one performed during another procedure, such as mitral valve surgery or coronary artery bypass grafting. A stand-alone minimally invasive surgical AF procedure is performed solely for the arrhythmia. Lone surgical AF procedures can also be described as open (typically via a sternotomy) or minimally invasive (nonsternotomy) with or without cardiopulmonary bypass (CPB). A hybrid procedure is a minimally invasive surgical procedure followed by a catheter-based ablation, or vice versa. Finally, a minimally invasive LAA closure can be performed to eliminate the risk of AF-related stroke and need for chronic anticoagulation therapy.

Having performed minimally invasive surgical treatment of atrial fibrillation (AF) for two decades, I explain five concepts that may help physicians and patients navigate these approaches. First, concomitant surgical AF procedures can be performed with a bipolar radiofrequency (RF) clamp involving a short operative time and with durable results compared with the older “cut and sew” Maze procedure. In this newer procedure, often termed a Cox-maze IV procedure, all ablative lesions are created with a bipolar RF clamp with or without cryothermia.¹ Second, minimally invasive beating-heart (off-pump) surgical AF procedures can be performed reliably with very low morbidity and mortality and with durable results out to 6 or more years.^{2,3} Third, AF hybrid procedures improve the efficacy of catheter-based approaches but usually involve two procedures.⁴⁻⁸ Fourth, there is ample evidence that vagal AF may be caused by an imbalance of the autonomic nervous system. The heart is awash with both parasympathetic and sympathetic autonomic fibers, which are abundant around the pulmonary veins (PVs) and the ligament of Marshall (LOM).

These autonomic nerves—ie, the ganglionic plexi (GP)—surround the PVs and can initiate AF. Ablating these GP reliably terminates AF.⁹⁻¹² Finally, new technologies that can provide transmural lesions around the left atrium (LA) in seconds are currently in clinical trials. This review explores these five concepts in detail.

TYPES OF SURGICAL PROCEDURES

Concomitant Surgical Atrial Fibrillation Procedures

For years, surgeons have relied on the Cox-maze procedure to treat AF in patients undergoing concomitant open-heart surgery. However, the technique was rarely used in the early days as it was rather complicated and added significant time to the procedure. By 1999, the Cox-maze procedure had evolved from a “cut and sew” to a cryothermia procedure. Even so, it was still seldom used by cardiac surgeons due to the added time to create multiple cryothermia lines on the atria (approximately 2 minutes for each freezing line on the heart).¹³

Beginning in 1999 and working with an electrical engineer (Michael Hooven), we designed a bipolar RF clamp that reliably created a transmural line on the atria in approximately 7 to 12 seconds—considerably faster than using cryothermia techniques on the heart (Figure 1). Using this new device, we demonstrated clinical utility in open concomitant mitral valve procedures in Europe in 2001 (Figure 2). Shortly thereafter, the clamp was available for concomitant AF open procedures in the United States. This bipolar RF clamp technology (Atricure®, Atricure, Inc) is now the global standard for creating transmural lesions on the atria during open-heart surgery. Efficacy (defined as AF-free at 1 year) in the 70% to 90% range has been demonstrated in multiple reports.¹⁴

After developing the bipolar clamp in the laboratory and during clinical use in 2001, this technology replaced the need for many



Figure 1.

Explanted porcine heart after bipolar clamp application externally on the beating heart. Transmural lesions are seen on the endocardium. Reprinted with permission from *Ann Cardiothorac Surg*, 2014.¹⁹

of the cryothermia lines. This dramatically reduced the time required for the AF procedure, leading to much wider adoption of the Cox-maze technique. Although the AF procedure is usually performed through a sternotomy, it can be performed through a left minithoracotomy during minimally invasive mitral valve repair or replacement. The open Cox-maze procedure is commonly performed during open mitral valve surgery but may be performed during almost any type of open-heart surgical procedure.

The percentage of patients receiving an AF surgery during a concomitant open-heart procedure is increasing. Although rare 15 years ago, concomitant AF surgery is now performed in about 60% of patients who have AF and are undergoing open-heart surgery.¹⁵

Minimally Invasive Surgical Atrial Fibrillation Procedures

A. Minimally Invasive Beating Heart Surgical Procedures

History and description. After 2 years of laboratory research, we performed the first stand-alone minimally invasive beating heart AF procedure in 2003 using the bipolar RF clamp technology. The procedure consisted of bilateral video-assisted thoracoscopic exposure of the LA, PVs, and LAA (Figures 3-6). The bipolar radiofrequency clamp that had been used for open procedures successfully isolated the LA. Acute entrance and exit block were recorded in each patient. The LAA was closed at its base with an endoscopic surgical stapler (Ethicon Endosurgery®).

The procedure was initially called “video-assisted bilateral PV isolation and LAA exclusion for atrial fibrillation.”² Within

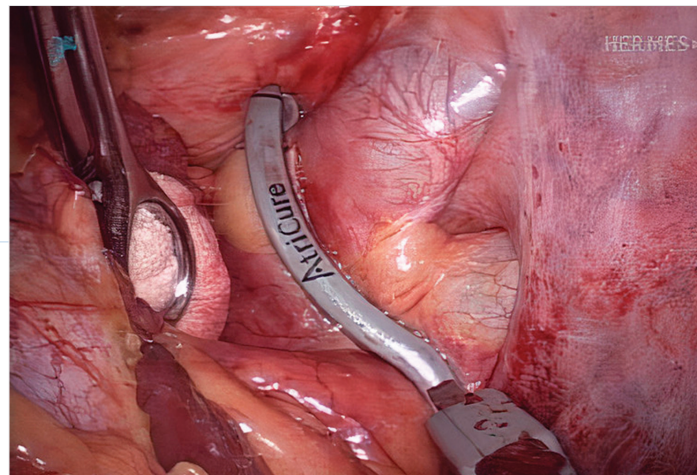


Figure 2.

Left superior and inferior pulmonary veins are visualized, and the dry bipolar clamp is seen on the left atrium. Reprinted with permission from *Ann Cardiothorac Surg*, 2014.¹⁹

1 year, in association with Drs. Scherlag and Jackman, we added testing and ablation of the GP to the procedure and demonstrated additional efficacy (Figure 7).¹⁶ Further research has confirmed that the GP plays an integral role in the initiation and maintenance of lone AF. It may be true that control of the autonomic nervous system around the PVs is more important than destruction of LA tissue. After several years of performing this minimally invasive procedure, a patient started a website describing the Wolf mini-maze for patients interested in AF surgery.¹⁷ Although the procedure is not actually a minimally invasive maze procedure, this common name has persisted. The current procedure consists of minimally invasive bilateral PV isolation with a bipolar RF clamp, testing and ablating the GP, documenting PV block, and closure of the LAA. Others have reported similar results for this technique.¹⁸

After more than 1,000 procedures using a stapler to close the LAA, we transitioned to clip closure of the LAA (Atriclip®, Atricure, Inc.). The Atriclip is as effective as a stapler and is somewhat more easily and quickly placed. In my personal experience, the mini-maze procedure is accomplished in approximately 90 minutes operating time (45 minutes on each side). The patient is awakened and extubated in the operating room. The average length of stay is 2.5 days. Patient activity is not restricted during the postoperative recovery period. The AF-free rate is 92% for paroxysmal AF, 85% for persistent AF, and 75% for long-standing persistent AF.^{19,20} Furthermore, patients do not need to resume anticoagulation therapy in the postoperative period unless they have indications other than AF for such therapy.

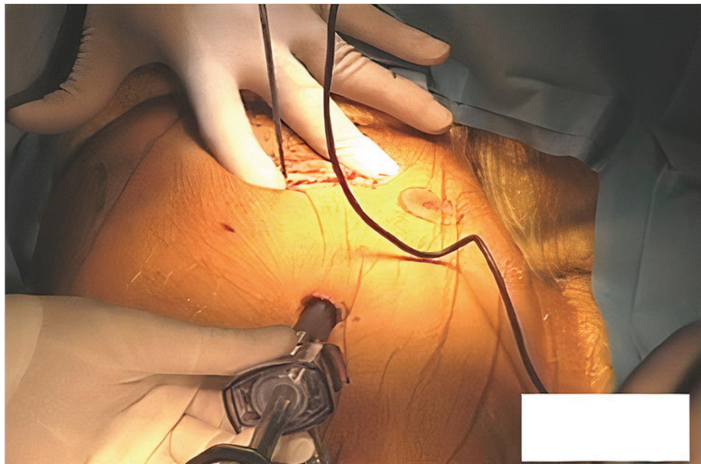


Figure 3. Right-sided video-assisted thoracoscopic approach with a scope in the inferior port and working port being created in the anterior fourth intercostal space. Reprinted with permission from Ann Cardiothorac Surg, 2014.¹⁹

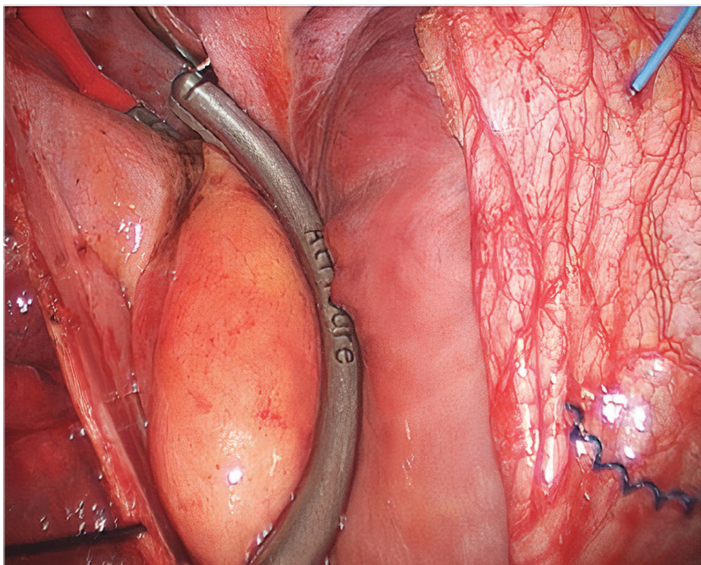


Figure 4. The septal lesion with a bipolar clamp encompassing the right side of the left antrum as well as a Waterston groove fat pad; this extends from the base of the superior vena cava superiorly to the base of the inferior vena cava inferiorly. To the right is a bipolar pacing lead inside of the pericardium. Reprinted with permission from Ann Cardiothorac Surg, 2014.¹⁹

In addition, cerebral microemboli during the mini-maze procedure are almost absent compared with the thousands of microemboli measured during catheter ablation. In one report, cerebral microembolic signals (MES) detected using transcranial Doppler

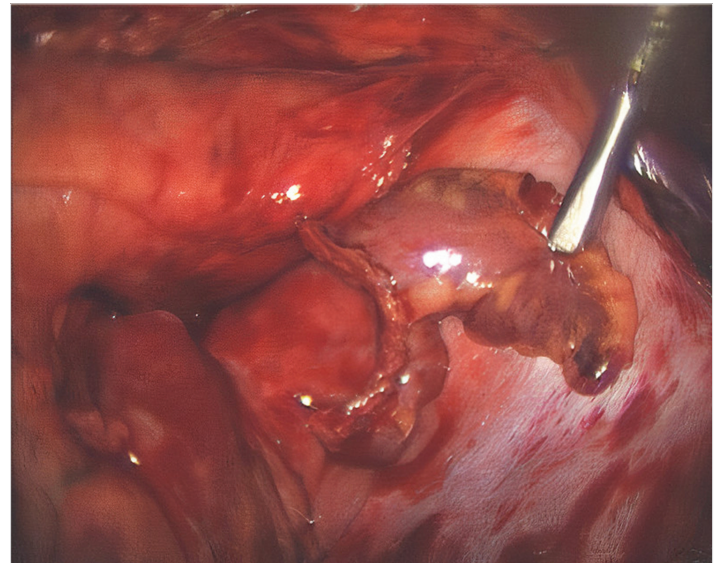


Figure 5. The stapled left atrial appendage is being removed from the intrapericardial area. Reprinted with permission from Ann Cardiothorac Surg, 2014.¹⁹



Figure 6. Intraoperative photograph demonstrating the position of the camera port with a chest tube and a 6-cm working port in the fourth intercostal space anteriorly. Reprinted with permission from Ann Cardiothorac Surg, 2014.¹⁹

technology exceeded an average of 2,500 during catheter ablation compared with an average of only one MES detected during the mini-maze approach.²¹ Additional reports suggest a correlation between the number of cerebral MES and neurologic impairment including stroke.^{22,23}

Many cardiac surgeons who perform the minimally invasive mini-maze procedure use the term “TT (totally thoracoscopic) maze.”

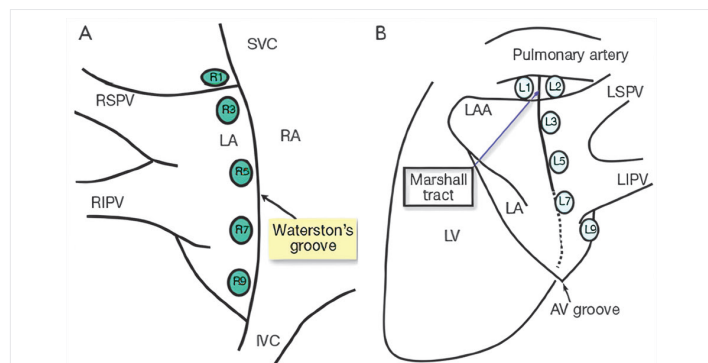


Figure 7.

The usual testing areas for ganglionic plexi (GP) activity on the (A) right side and (B) left side of the left atrium.¹⁹ SVC: superior vena cava; RSPV: right superior pulmonary vein; RIPV: right inferior pulmonary vein; LA: left atrium; RA: right atrium; IVC: inferior vena cava; LAA: left atrial appendage; LSPV: left superior pulmonary vein; LV: left ventricle; LIPV: left inferior pulmonary vein; AV groove: auriculoventricular groove

This simply means that the bilateral 5-cm to 6-cm incisions for the working ports are replaced with two smaller ports on each side. Notably, the duration of the TT maze procedure is generally twice as long as the mini-maze, with some risk for the complication of phrenic nerve injury.²¹ Also, many surgeons who use the TT approach fail to perform the critically important GP portion of the procedure. Although some of the GP are isolated by the clamping technique alone, and some on the left side are addressed by dividing the LOM, we have shown that additional GP are located outside of the clamp area. Thus, complete GP denervation requires additional attention. An important aspect of the mini-maze technique is ablation of these with a bipolar pen.

Candidate selection. Suitable candidates include: (1) patients with previous (failed) catheter ablations; these patients require a computed tomography (CT) scan in the preoperative period to rule out PV stenosis; (2) patients with previous AF-related stroke; these patients require a CT scan in the preoperative period to rule out thrombus in the LA and/or LAA; and (3) patients who prefer a surgical approach over catheter ablation for initial treatment after failed medications and /or cardioversions. Patients who have had previous open-heart surgery may also be candidates for a mini-maze procedure unless they underwent previous mitral surgical procedures. The presence of a permanent pacemaker does not interfere with the mini-maze procedure.

Preoperative testing. This should include transthoracic or transesophageal echocardiography examination (within 12 months), an electrocardiogram (ECG) documenting the arrhythmia, a CT scan in selected patients (eg, previous catheter ablation, previous stroke and or coronary disease), and stress testing in selected patients (Table 1).

IMAGING/TEST	PURPOSE
Electrocardiograph	Document rhythm
Echocardiogram	Measure size of left atrium; confirm valve function
64-slice computed tomography	Visualize anatomy of pulmonary veins (PV) and left atrial appendage; identify possible thrombus, PV stenosis, coronary anatomy and pathology
Home monitoring (if needed)	Document atrial fibrillation burden

Table 1.

Different tests used during treatment of lone atrial fibrillation.

Medication management. Antiarrhythmic therapy should be continued up until the morning of surgery. Anticoagulant therapy should be discontinued 2 days before surgery. Patients with a history of stroke may be bridged with subcutaneous heparin. Novel oral anticoagulants (NOACs) may be discontinued after LAA closure with a stapler or Atriclip. Generally speaking, administration of NOACs reduce the incidence of AF-related stroke by decreasing hemorrhagic strokes compared to warfarin,²³ whereas complete LAA closure with a stapler or an Atriclip reduces the incidence of all types of AF strokes by 97%.²⁴ Unlike the Atriclip, another popular LAA occlusion device (Watchman®) has a relatively high postprocedure stroke risk; thus, US Food and Drug Administration regulations require anticoagulation for several weeks after Watchman insertion.²⁵ Closure of the LAA with a stapler or Atriclip provides complete electrical isolation of the LAA, whereas the Watchman device does not electrically isolate the LAA.

For management of antihypertensive medications, chronically elevated blood pressure is reduced after LAA closure, with persistent decreases in angiotensin blood levels.²² We are routinely able to decrease antihypertensive medications after the mini-maze, often with complete elimination of antihypertensive medications in many previously hypertensive patients.

Monitoring and management of postoperative arrhythmias. An implantable loop recorder (LINQ®, Medtronic, Inc) is placed 1 week postoperatively in patients without a previously implanted loop recorder or pacemaker. Monitoring the loop recorder allows weaning of antiarrhythmics as feasible, with follow-up continuing for up to 4 years. Occasionally, a patient requires a cardioversion approximately 1 month after the procedure, usually for atrial flutter but sometimes for AF (typically in those with a long history of chronic AF). In

some cases, a persistent right-sided atrial flutter ablation is required. Cardioversion is very effective for patients who have postoperative AF or atrial flutter, and antiarrhythmics can typically be weaned and discontinued over the subsequent 90 days.

B. Minimally Invasive On-Pump Surgical Procedures

A minimally invasive technique can also be performed using CPB.^{26,27} This is named the minimally invasive Cox-maze IV and is similar to the open Cox-maze procedure. The difference is that the sternotomy is replaced by a left minithoracotomy, and venous and arterial cannulation for CPB is accomplished via the femoral vessels. A left minithoracotomy allows direct vision of the LA, and both the right and left atria are opened in this on-pump procedure while the heart is arrested. Standard Cox-maze IV procedures include isolation lines on the right atrium and the LA. The lesions are created with a combination of bipolar clamp lines and cryothermia lines (Figure 8).

Most of these procedures are not stand-alone procedures but are performed as a concomitant procedure during minimally invasive mitral valve repair or replacement. Cox-maze IV results are institution dependent. In one multicenter study, freedom from AF off antiarrhythmic medications at 1, 2, and 3 years was 66%, 65%, and 64%, respectively, and including those using antiarrhythmics was 80%, 78%, and 76%, respectively.²⁸

Compared to minimally invasive off-pump procedures such as the mini-maze, a disadvantage of minimally invasive on-pump AF procedures is the potential for other surgical complications related to groin access, which is necessary when using large-bore vascular cannulation for CPB. A

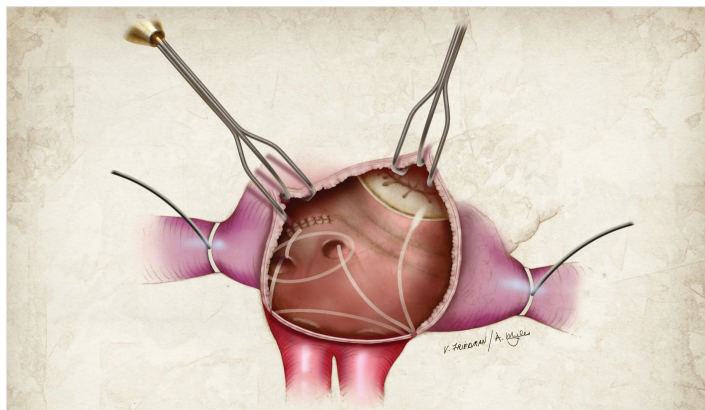


Figure 8. Minimally invasive left-sided Cox Maze 4. Through a right thoracotomy, on bypass and open heart, a sequence of left atrial endocardial cryo and radiofrequency ablations are depicted. Reprinted with permission from AtriCure.

proposed advantage of minimally invasive on-pump is improved AF-free status at 1 year compared with off-pump AF procedures. However, results are center- and surgeon-specific, with overlap in AF-free incidence.¹⁴

Left Atrial Appendage Closure for Stroke Prevention

In some patients, it is unreasonable to perform the complete mini-maze procedure due to patient-related factors such as continuous AF for > 5 years, LA size > 5.5 cm, or advanced age. In such patients, we perform a stand-alone minimally invasive technique using Atriclip LAA closure. This 30-minute procedure allows consistent and complete closure of the LAA with excellent stroke prevention (Figure 9).

Hybrid Procedures

A hybrid procedure generally refers to a minimally invasive surgical procedure followed by a catheter-based ablation.

Mini-maze procedure. If the patient is still in AF 6 to 12 months after a mini-maze procedure, a follow-up catheter ablation can be performed. This is highly effective since the PVs have been transmurally completely isolated, all GP have been ablated, and the LAA has already been closed.²⁸ The follow-up catheter ablation can then focus on any areas outside of the mini-maze (eg, perimitral valve area, Coumadin ridge).

TT maze procedure. In Europe, there is one series of patients in which the AF was treated concomitantly with a TT maze and a catheter ablation, with similar good results to those of the on-pump maze or mini-maze procedures.⁴ However, use of this concomitant approach is uncommon.^{5,6}

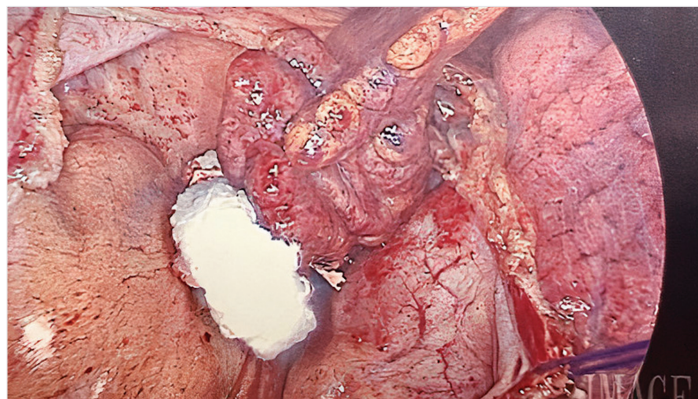


Figure 9. For patients who cannot undergo a complete mini-maze procedure, a stand-alone minimally invasive technique using Atriclip left atrial appendage (LAA) closure allows consistent and complete closure of the LAA with excellent stroke prevention. In this operative photograph, the white Atriclip is seen at the base of the LAA.

Convergent procedure. In the last few years in the United States, there has been an increase in hybrid AF procedures consisting of a subxiphoid minimally invasive surgical approach followed a few months later by a catheter ablation. This is known as the “convergent procedure.”^{7,8} The surgeon’s main focus is to isolate the posterior wall of the LA so that this area can be avoided during the subsequent catheter-based procedure. Avoiding this posterior LA area during the catheter-based procedure is thought to decrease the most dreaded complication from catheter ablation (LA-to-esophageal fistula), while increasing the extent and completeness of the posterior LA wall ablation (the surgical portion of the technique).

Disadvantages of the convergent procedure include destruction of a large part of the LA, inattention to the LAA, lack of GP ablation, and a reliance on catheter ablation for some or all of the PV isolation. Some surgeons have added LAA closure to the convergent procedure via a separate left-sided thoracic approach. However, it seems short-sighted to approach the LA from the left chest to close the LAA without simultaneously including division of the LOM, GP ablation, and isolation of the left PVs.

In a trial of the convergent procedure with a subxiphoid approach and simultaneous catheter ablation, LA-to-esophageal fistula complication was reported.²⁹ Therefore, almost all convergent procedures are now completed by performing the surgical procedure first, followed by the catheter ablation a few months later.

TREATMENT OF VAGAL ATRIAL FIBRILLATION

There are numerous animal experiments demonstrating the importance of the GP in AF initiation and maintenance.^{9-12,30} It is possible that most stand-alone cases of AF in humans begin with what is termed “vagal AF,” in which an imbalance of the autonomic nervous system results in overstimulation of the GP, which are 80% mixed sympathetic and parasympathetic (Figure 10).³¹ We routinely test the GP (which are abundant in the fat around the PVs) with high-frequency stimulation during the mini-maze procedure. Such stimulation results in an immediate vagal response, leading to ventricular diastolic arrest that is immediately reversed by simply terminating GP stimulation. These active GP areas are located around the PVs and in the LOM (Figure 11).³² After ablating the GP, the GP areas are stimulated again. If there is no slowing of the ventricular response defined by a 50% slowing of the R-to-R interval (heart rate), then the GP are determined to be isolated. Ablating these GP areas improves the success rate of PV isolation (Figure 12).^{15,33} Logically, it follows that extensive destruction of the LA may be a poor substitute for a complete GP ablation. The importance of targeting GP ablation of the LOM during catheter-based approaches has also been noted by some investigators.³⁴

EVOLVING SURGICAL TREATMENT TECHNOLOGIES

Pulsed Field Ablation

Pulsed field ablation (PFA) is a nonthermal ablative modality in which ultra-rapid (< 1 sec) electrical fields are applied to the LA tissue. This destabilizes cell membranes by forming irreversible nanoscale pores and leakage of cell contents that result in cell death.³⁵ The IMPULSE study (A Safety and Feasibility Study of the IOWA Approach Endocardial Ablation System to Treat Atrial Fibrillation) used this technology for endocardial ablation.³⁵ This technology is also being tested for surgical epicardial ablation. The time required to complete a transmural lesion is only a few seconds, and surrounding tissue appears to be spared. Research involving a surgical bipolar clamp application of this technology is underway.

Epicardial-Endocardial Ablation

Another experimental technique involves simultaneous epicardial and endocardial ablation, with alignment of the epicardial and endocardial devices to create transmural lesions. The epicardial device may be placed via a subxiphoid approach using new technology. One such device, the CardioScout®, will provide epicardial access via a subxiphoid approach to several areas on the beating heart, including the atria, ventricles, and LAA (Figure 13).

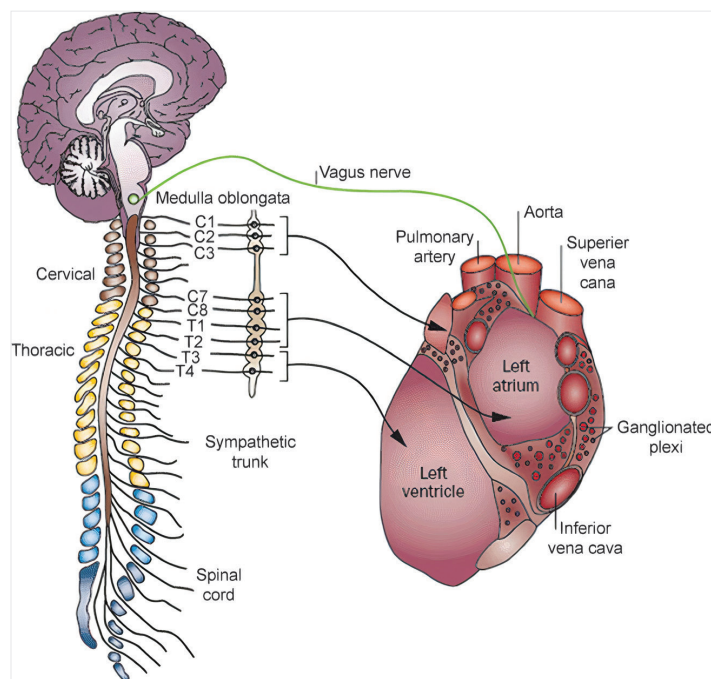


Figure 10. Sympathetic and parasympathetic innervation of the heart. Reprinted with permission from Springer Nature.³¹

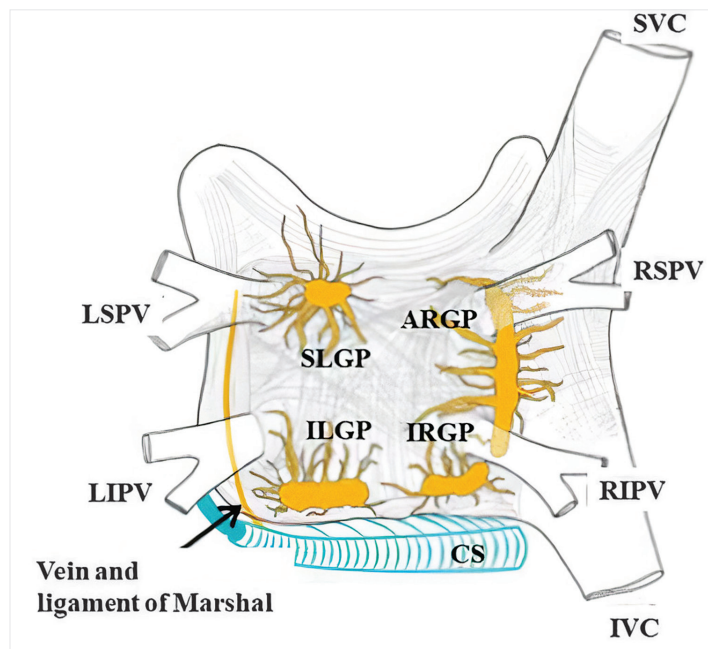


Figure 11. Active ganglionic plexi areas on the outside of the left atrium are shown in yellow.³² LIPV: left inferior pulmonary vein; LSPV: left superior pulmonary vein; RSPV: right superior pulmonary vein; RIPV: right inferior pulmonary vein; IVC: inferior vena cava

Novel Atrial Defibrillation

My current research efforts include a technology that allows for atrial defibrillation with ultra-low energy (0.5 to 2 Joules). Initially, the device (Native Cardiovascular, Inc.) will be placed during an open-heart surgical procedure, with future plans to place it through smaller incisions. This much smaller energy output for atrial defibrillation may not require patient sedation for cardioversion.

CONCLUSION

Twenty years ago, there were few surgical options for patients with AF, and most patients were told there was little to be done to eliminate blood thinners or stop AF altogether. However, surgical treatment of AF has evolved considerably since then, providing hope to many patients who have this common arrhythmia. Over the past two decades, it has become more common to address AF during open-heart surgery, and minimally invasive stand-alone procedures for AF are now available. The pace of evolution for AF procedures will undoubtedly increase in the next decade. Because of newer procedures for LAA closure, some patients are able to safely discontinue anticoagulation therapy with reduced stroke risk. Even better, they have the possibility of remaining free of AF for years after a surgical procedure.

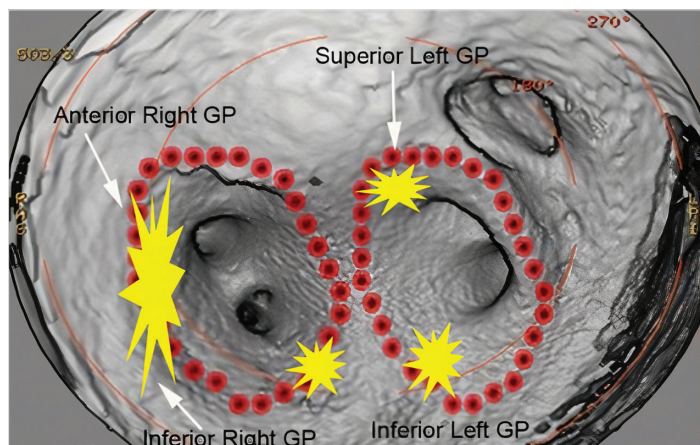


Figure 12. Active ganglionic plexi areas are depicted in yellow. As shown on the inside of the left atrium, these areas are actually on the epicardial surface. Image courtesy of Jeff Williams, MD.

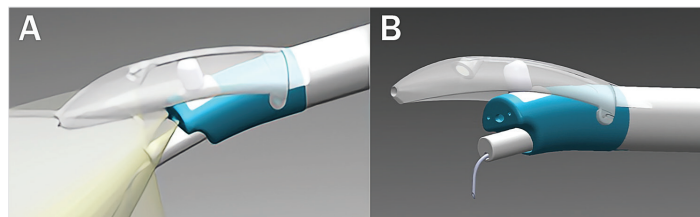


Figure 13. The CardioScout device includes (A) a tiny light source, camera, and (B) working ports for epicardial visualization of the beating heart. Images courtesy of James Fonger, MD.

KEY POINTS

- Compared to 20 years ago, there are now several surgical options clinically available to treat atrial fibrillation (AF), including open-heart Cox-maze IV, as well as several nonsternotomy and hybrid procedures.
- Newer procedures for left atrial appendage closure allow patients to safely discontinue anticoagulation therapy with reduced stroke risk.
- Clinicians should understand and be able to articulate all current treatments available to their patients with AF.

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Conflict of Interest Disclosure:

Dr. Wolf consults for and conducts research on behalf of AtriCure, Inc., and Native Cardiovascular, Inc.

Keywords:

atrial fibrillation, Cox-maze procedure, mini-maze

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