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Surgery for Atrial Fibrillation

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Synopsis

Atrial fibrillation is the most common cardiac arrhythmia and its treatment options include drug therapy or, catheter-based or surgical interventions. The surgical treatment of atrial fibrillation has undergone multiple evolutions over the last several decades. The Cox-Maze procedure which was developed by James Cox in 1987 is a procedure where multiple surgical incisions are created along the atria to interrupt the electrical pathways thought to allow atrial fibrillation to persist. This procedure went on to become the gold standard for the surgical treatment of atrial fibrillation and is currently in its 4th iteration called the Cox-Maze IV. The Cox-Maze IV replaced the previous “cut-and-sew” method with a combination of cryoablation and bipolar RF ablation. The adaption of ablation technologies allowed the Cox-Maze IV procedure to be performed through a less invasive right minithoracotomy instead of a traditional sternotomy approach. The aim of this article is to review the indications and preoperative planning for performing a Cox-Maze IV procedure. A description of the operative techniques for both a sternotomy and right mini-thoracotomy approach will be discussed in addition to specific postoperative considerations. Finally, this article will review the literature describing the surgical results for both approaches including comparisons of the Cox-Maze IV to the previous “cut-and-sew” method.

Keywords

Cox-Maze; Atrial Fibrillation; Surgical Ablation; Minimally Invasive

Introduction

Atrial fibrillation (AF) remains the most common arrhythmia, affecting more than 5 million people in the United States alone. With the aging population, the prevalence of AF has

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increased over the past decade, and is expected to double by the year 2030¹. Despite advances in treatment, AF still carries significant morbidity and mortality that stem from two major mechanisms: 1) asynchronous atrioventricular contractions, which results in varying degrees of hemodynamic compromise and 2) stasis of blood in the atria that predisposes patients to clotting and subsequent thromboemboli². The risk of stroke in patients with AF has been shown to be increased by as much as 5-fold³. Most AF patients require anticoagulation, and despite the introduction of direct factor Xa inhibitors, anticoagulation predisposes to other major morbidities including GI bleed and hemorrhagic stroke⁴.

The treatment of AF represents a significant economic burden with an estimated \$26 billion spent annually in the United States⁵. Antiarrhythmic medications have been the mainstay of treatment for nearly 100 years, but their use has been limited by systemic toxicity, low efficacy, and arrhythmogenicity⁶. Pharmacotherapy is routinely directed at either controlling the patient's rhythm or ventricular rate. The Atrial Fibrillation Follow-up Investigation of Rhythm Management (AFFIRM) study demonstrated that management with rhythm control had no survival benefit over rate control in anticoagulated patients⁷; however, there was a clear survival benefit for patients that were able to achieve normal sinus rhythm.⁸ The pharmacological inadequacies of treating atrial fibrillation have justified a role for interventional management of atrial fibrillation.

Starting in the 1980s, several procedures were developed in an effort to treat atrial fibrillation including left atrial isolation,⁹ corridor operation,¹⁰ and atrial transection.¹¹ However, these procedures were abandoned because of their inability to reliably prevent or cure atrial fibrillation in humans. It was not until 1987 that a team led by Dr. James Cox devised the "Maze" procedure, now known as the "Cox-Maze Procedure", which reliably and successfully treated AF.¹¹ This review aims to discuss the indications for surgical ablation of AF, the technique and results of the Cox-Maze IV (CMIV) procedure.

Indications for Surgical Ablation of Atrial Fibrillation

In 2007, a Task Force that included the Society of Thoracic Surgeons, American College of Cardiology, Heart Rhythm Society, European Heart Rhythm Association, and European Cardiac Arrhythmia Society was established to create a consensus statement on AF surgical and catheter-based treatment.¹² Over the past several years there has been a large volume of literature evaluating the efficacy and safety of not only catheter-based ablation, but also surgical ablation. Also, the advent of ablation technology has allowed for greater flexibility of the surgical approach and has expanded the indications, particularly for concomitant AF procedures in patients undergoing other cardiac surgery.

The Task Force re-convened in 2012 and released the consensus indications for surgical ablation divided into two separate categories: those patients undergoing concomitant cardiac surgery and those having stand-alone surgical treatment of their AF.¹³ For those undergoing other cardiac surgical procedures, all patients with symptomatic atrial fibrillation should be considered for surgical ablation, regardless of whether antiarrhythmic medications have been started. Ablation should also be considered in selected asymptomatic patients in whom

adding an ablation procedure would not add to operative morbidity or mortality. However, stand-alone surgical ablation is generally indicated in patients with symptomatic AF who have failed medical therapy and either have failed one or more catheter ablations or prefer surgical therapy.¹³

Surgical Technique: Cox-Maze IV Procedure

Preoperative Planning

To simplify the CMIII, our group at Washington University replaced the majority of the “cut-and-sew” lesions that comprised the CMIII with a combination of bipolar radiofrequency ablation and cryoablation and have termed the revision the CMIV. All patients receive a transthoracic echocardiogram (TTE) to determine left atrial (LA) size and the presence of valvular disease. LA size in particular is important since LA diameter is a strong predictor of procedural success, with a diameter of ≥ 8 cm associated with a failure rate of greater than 50%.¹⁴ While TTE also can be used to evaluate for the presence of LA clot, this needs to be confirmed intraoperatively with transesophageal echocardiography. In patients who have failed catheter ablation, a contrast chest CT scan is obtained to evaluate the pulmonary veins.

This procedure can be performed through either a sternotomy or a less invasive right mini-thoracotomy (RMT). Our group prefers a RMT approach in the absence of contraindications which include previous right thoracotomy, severe atherosclerotic disease of the aorta, iliac or femoral vessels, and severely decrease left ventricular ejection fraction (LVEF $\leq 20\%$). All patients scheduled to have a RMT receive a CT angiogram of the thoracic and abdominal aorta as well as the femoral arteries if they are over the age of 40, have risk factors for the development of peripheral vascular disease (PVD) or demonstrate evidence of PVD on physical examination. An RMT approach can be used in patients receiving a concomitant mitral or tricuspid valve procedures. Other concomitant procedures such as aortic valve replacement are performed through a sternotomy approach.

Positioning

Positioning is dependant on the approach being used. In a sternotomy approach, patients are placed supine with both arms tucked. In an RMT procedure, the patient is intubated using a bronchial blocker placed in the right main stem bronchus allowing for right lung deflation. The patient is then placed supine with the hips flat but the right chest elevated 30–45°. The right arm is placed over the head in anatomic position with the aid of an arm board and the left arm is tucked. Both groins are prepped with antiseptic solution in the RMT approach in preparation for femoral cannulation (Figure 1).

Operative Technique

There are several important differences between the sternotomy and RMT approach. An outline of each approach and its lesions sets are listed below followed by a description of the key operative steps. It should be noted that each RF ablation line is created by performing 2–3 firings of the bipolar RF clamp. This is done in order to assure a transmural lesion.¹⁵

Sternotomy Approach

- Median sternotomy, central cannulation of SVC, IVC, and aorta, and initiation of cardiopulmonary bypass (CPB)
- Right and left pulmonary vein isolation (PVI)
- Right atrial (RA) lesion set (Figure 2A)
 - Purse string at the base of the RA appendage
 - Bipolar RF ablation line through this purse-string toward SVC on the aortic side of the appendage
 - Right vertical atriotomy
 - Bipolar RF ablation lines from the inferior aspect of the atriotomy up to the SVC and down to the IVC
 - Linear endocardial cryoablation from superior aspect of atriotomy to 2'o clock position of the tricuspid valve (TV) annulus
 - Linear endocardial cryoablation from RA pursestring to 10'o clock position of TV annulus
 - Placement of retrograde cardioplegia catheter in the coronary sinus (CS) and closure of right atriotomy
- Cardioplegic arrest with antegrade/retrograde cardioplegia
- Left atrial (LA) lesion set (figure 2B)
 - LA appendage amputation and bipolar RF ablation to left superior PV
 - Mark CS with methylene blue between the right and left coronary circulations
 - LA atriotomy
 - Bipolar RF ablation connecting lesions from the inferior aspect of the atriotomy into the left inferior PV and from the superior aspect of the atriotomy into the superior PV
 - Bipolar RF ablation from inferior aspect of atriotomy toward mitral valve (MV) annulus and across the CS
 - Endocardial cryoablation to connect the end of this bipolar RF ablation to the MV annulus
 - Simultaneous epicardial linear cryoablation over the coronary sinus to complete the mitral isthmus ablation

Pulmonary Vein Isolation: Intraoperatively, the absence of LA clot is confirmed with transesophageal echo (TEE) in all patients. A median sternotomy is performed and cardiopulmonary bypass is initiated. Both the right and left PVs are bluntly dissected after the initiation of normothermic CPB. If a patient happens to be in AF at the time of the

surgery and there is no LA clot, they are electrically cardioverted after administration of IV amiodarone. Pacing thresholds are measured from each PV. The right and left PVs are then isolated using a bipolar RF clamp. Three ablations are performed for each lesion and the clamp is moved slightly between each ablation ensure electrical isolation between the PVs and the rest of the rest of the LA. It is important to clamp a generous cuff of atrial tissue between the jaws of bipolar RF clamp in order to complete the PVI. Isolation is confirmed by documenting exit block demonstrated by a failure to epicardially pace from each of the pulmonary veins.

Right Atrial Lesion Set: The patient is then cooled to 34°C and the RA lesion set is performed on the beating heart (Figure 2A). A small purse-string suture is placed at the base of the RA appendage, wide enough to accommodate one jaw of the bipolar RF ablation clamp. An ablation lesion is created with the bipolar clamp across the free wall of the RA down towards the SVC on the aortic side of the right atrial appendage. A vertical atriotomy then is made from the intraatrial septum up towards the AV groove near the free margin of the heart. This incision should be at least 2 cm from the first free wall ablation in order to avoid an area of slow conduction. A linear cryoprobe is used to create an endocardial cryoablation from the superior aspect of this incision down to the tricuspid annulus at the 2'o clock position. All cryoablations are performed for three minutes at a temperature below 40° C. Cryoablation is ideal to complete lesions over annular tissues because it preserves the fibrous skeleton of the heart therefore maintaining valve competency. The linear cryoprobe is then inserted through the previously placed purse-string and an endocardial cryoablation is created down to the tricuspid valve annulus at the 10'o clock position. The RF ablation clamp is used to create ablation lines running from the inferior aspect of the right atriotomy up along the lateral aspect of the SVC and down to the IVC.

Left Atrial Lesion Set: At this point, the LA lesion set is performed. (Figure 2B) The aorta is cross clamped and the heart is arrested using cold blood cardioplegia. The heart is retracted, and the LA appendage (LAA) is amputated. Through the amputated LAA, the bipolar RF clamp is used to create an ablation line to either of the left PVs. The LAA is oversewn in two layers with a 4-0 Prolene suture. The CS is marked with methylene blue at a position between the posterior descending artery and the terminal branch of the circumflex artery. A standard left atriotomy is performed connecting to the previous right pulmonary vein isolation. The entire posterior left atrium is then isolated by using the bipolar RF ablation clamp. The first ablation line is placed from the inferior aspect of the atriotomy across the floor of the LA into the left inferior PV. A second ablation line is created from the superior aspect of the atriotomy across the roof of the LA into the left superior PV. A final bipolar RF ablation is placed from the inferior aspect of the atriotomy, across the atrial floor of the LA, toward the mitral valve annulus. This ablation is aimed toward the P2 scallop of the posterior mitral leaflet in the majority of patients who have a right dominant circulation and should cross the coronary sinus at the area previously marked with methylene blue. An endocardial cryoablation is then performed to connect this ablation line to the mitral valve annulus at the end of the mitral isthmus lesion. To complete the LA isthmus ablation, a simultaneous epicardial cryoablation is performed over the coronary sinus in line with the endocardial lesion.

Right Mini-Thoracotomy Approach

Right Mini-Thoracotomy Approach Outline

- Subinguinal incision and femoral Cannulation
- 5–6mm RMT at 4th intercostal space
- Initiation of CPB
 - Right lung deflation
 - Insertion of 5mm port in posterior-axillary line at the 6th intercostal space for 30° endoscope
- Right pulmonary vein isolation
 - Right PVI using bipolar RF clamp. Three ablations are recommended.
 - Pacing is used to document exit block from each of the right PVs
- RA lesion set
 - RA pursestring #1 between SVC/IVC, bipolar RF ablation lines are made up to SVC and down to IVC
 - The bipolar RF clamp is placed through pursestring #1 to create an ablation line up the RA free wall towards the AV groove, approximately at the free margin of the heart.
 - RA pursestring #2 is placed at the superior aspect of this free wall bipolar RF ablation
 - A linear endocardial cryoablation through pursestring #2 down to the 2 o'clock position of TV annulus
 - RA pursestring #3 at base of RA appendage, bipolar RF ablation of RA free wall toward SVC along the aortic side of the RA appendage
 - A second linear endocardial cryoablation through pursestring #3 down to the 10 o'clock position of TV annulus
- Aortic cross clamp placed through right lateral chest wall
 - Antegrade cardioplegia needle in the proximal ascending aorta
 - Cold antegrade cardioplegic arrest
- LA lesion set
 - Right anterior chest wall stab incision for placement of left atrial lift system through 4th intercostal space
 - Left atriotomy and placement of left atrial lift system
 - Endocardial LA appendage closure

- Bipolar RF ablation connecting lesions from the inferior aspect of the atriotomy into the left inferior PV and from the superior aspect of the atriotomy into the superior PV
- Endocardial cryoablation to connect these to ablation lines going behind the left PVs, isolating the entire posterior LA.
- Bipolar RF ablation from inferior aspect of atriotomy toward MV annulus and across the CS
- Endocardial cryoablation to connect the end of this bipolar RF ablation to the MV annulus
- Simultaneous epicardial linear cryoablation over the coronary sinus to complete the mitral isthmus ablation

A video and illustrated description of our RMT approach has previously been published.^{16, 17} While there are several obvious differences between the sternotomy and RMT approaches, the lesion set in the RMT approach remains the same. Initial differences between these approaches are establishment of femoral cannulation for CPB under TEE guidance and the need to deflate the right lung to facilitate a minimally invasive exposure. The RA lesion set has been modified with replacement of the atriotomy with a line of bipolar RF ablation while the other RA lesions are performed through 3 separate pursestring sutures. The LA lesion set is identical with 2 exceptions. Left pulmonary vein isolation is achieved by sequential endocardial cryoablation connecting the superior and inferior connecting box-lesions behind the left pulmonary veins usually along the lateral ridge, since epicardial isolation of the left pulmonary veins is difficult through a right mini-thoracotomy. Lastly, exclusion of the LAA in the RMT approach is achieved by oversewing endocardially in two layers as opposed to epicardial amputation which is performed in the sternotomy approach.

Perioperative and Postoperative Management

Perioperative management is similar between both approaches. Considerations unique to the CMIV procedure include postoperative arrhythmias including junctional and atrial tachyarrhythmias (ATAs). Epicardial pacing wires which are left on the RA and right ventricle at the end of the procedure are used to pace the atria at 80–100 beats per minute. The atrial wires are helpful in diagnosing atrial arrhythmias, since the p wave can be small and difficult to see after a CM procedure. If heart block develops, AV sequential pacing (DDD mode) is used. Junctional rhythms which are present in the majority of patients postoperatively usually resolve without intervention after several days. Antiarrhythmic medications should not be started until patients develop sinus rhythm, particularly in patients with bradyarrhythmias. Approximately 5% of patients will fail to recover sinus rhythm and require a permanent pacemaker following a CMIV procedure and the incidence of pacemaker implantation increases with patient age.¹⁸ Approximately half of patients will develop ATAs postoperatively and usually resolve after the 1st postoperative month. Patients with stable ATAs are usually rate controlled pharmacologically and are DC cardioverted if

ATAs persist. It is best to wait 1–3 weeks after surgery prior to cardioversion, if possible, to allow the inflammation to subside.

The final consideration is the initiation of anticoagulation. Warfarin is started post operatively in all patients receiving a CMIV procedure and is continued for at least 3 months postoperatively in the absence of contraindications. If after a 3 month blanking period the patient has no ATAs off antiarrhythmic medications on prolonged monitoring (at least a 24 hour Holter), and demonstrates no atrial stasis on echocardiography, we recommend the discontinuation of warfarin.¹⁹ Using this approach, we have had a very low stroke risk after the CM procedure even in patients with high CHADS₂ scores.

Surgical Results: Cox-Maze IV Procedure

The CMP has long been considered the gold standard in surgical ablation and continues to be the interventional procedure with the single highest success rate of terminating atrial tachyarrhythmias (ATA). There have been several studies documenting the long-term efficacy of the CMP. One study from our own institution looked at the results of 187 patients who received the CMP. This study showed a 97% freedom from symptomatic AF at 5.4 years. This same study showed no difference in recurrence when comparing patients who received a standalone CMP versus patients who received a concomitant procedure.²⁰

The excellent long term efficacy of the CMPIV has also been reported. Our group prospectively followed 100 patients who received a lone CMPIV procedure. Follow-up was scheduled 3, 6, and 12 month intervals and annually thereafter. Most patients were evaluated with 24hr Holter monitoring and when not available an ECG. Patients were considered to have late recurrence if there was any episode of AF, atrial flutter, or atrial tachycardia lasting longer than 30 seconds. The mean follow up time was 17±10 months. Thirty one percent of patients had paroxysmal AF, 6% had persistent AF, and 63% had longstanding persistent AF. This study showed that at both 12 and 24 months, 90% of patients were free from ATAs while 82% were free from ATAs and off antiarrhythmic medications.²¹ In a separate study, this same group was then retrospectively compared to 112 patients who had a lone CMP procedure from 1992 to 2002. In the CMP group, late recurrence was determined by measuring only symptomatic AF at follow-up which likely overestimated the procedure's success. This comparison showed no difference in freedom from AF off antiarrhythmic medications between the CMP group and CMPIV group (83% vs 82%).²²

The CMIV procedure has also been shown to be advantageous in the perioperative setting when compared to the CMP. Mean aortic cross clamp times were significantly decreased with a lone CMPIV compared to a lone CMP (39 minutes vs. 90 minutes). Mean concomitant cross clamp times have also been shown to be shorter when comparing the CMPIV to the CMP (99±30 minutes vs 122±37 minutes).^{20, 23} In addition, the CMPIV does have a significantly lower major complication rate compared to the CMP. In our previous series comparing the CMP to the CMPIV, major complication was defined as reoperation for bleeding, early stroke, renal failure, mediastinitis and need for intra-aortic balloon pump (10% vs 1%).²² There were no differences in 3 month pacemaker

implantation rate or 30 day mortality rate when comparing both versions of the procedure which were 7–8% and 1–2% respectively.²²

Originally the CMPIV lacked a posterior left atrial box-lesion set which was employed in 2005. Prior to this, only a single connecting lesion was used between the left and right inferior pulmonary veins. This was because there was initially concern that complete electrical exclusion of the entire posterior LA might have a detrimental effect on LA function. This thought has since been disproven with aid of cardiac MRI showing LA function is maintained with the addition of a box-lesion.²⁴ However, studies from our group comparing 78 patients with a true box-lesion set to 22 patients without a showed an increase in freedom from AF off antiarrhythmic medications (85% vs 47%) at greater than one year follow up.²¹ Because of this, all CMPIV at our institution now utilize the full box-lesion.

Atrial fibrillation is frequently coincident with other cardiac disease processes including coronary artery disease and valvular disease. The development of new ablation technologies associated with the CMIV took a technically difficult and time-consuming operation and made it relatively easy for all cardiac surgeons to perform. Whereas very few patients (<1%) with AF undergoing cardiac surgery before 2000 underwent a concomitant Cox-Maze procedure, a study has shown that more than 40% of patients with AF undergoing cardiac surgery had a concomitant ablation procedure in 2006.²⁵ More recent studies have demonstrated similar CMIV outcomes in patients with lone AF compared to receiving concomitant mitral procedures.²⁶ Specifically, freedom from AF and antiarrhythmic drugs at 12 and 24 months were nearly identical between the two groups (73% vs. 76% at 12 months; 77% vs. 78% at 24 months).²⁷

While there are reports of less invasive surgical ablation approaches, few groups have evaluated the long term outcomes using these approaches. Our group has developed a minimally invasive approach to the CMIV using a right mini-thoracotomy (RMT) approach. Early results using this approach have been promising when compared to the CMIV performed through a sternotomy.²⁸ More recent unpublished data has shown freedom from AF off antiarrhythmic drugs was not significantly different between the two groups at 1 and 2 year postoperatively. Furthermore, patients who underwent RMT had fewer complications, and both decreased ICU and hospital lengths of stay when compared to those patients who underwent a CMIV through a sternotomy. These results demonstrate that the CMIV performed through a RMT approach is as effective as sternotomy in the treatment of atrial fibrillation.

Risk factors for recurrence after performing a CMIV procedure at 1 year include 1) failure to perform a box-lesion, 2) increasing left atrial size, and 3) early ATAs.¹⁴ As discussed above, our group has previously shown that a full left atrial isolation via a box-lesion significantly reduced the recurrence of AF. This finding is in agreement with data from the electrophysiology laboratory which has shown that a wide area circumferential ablation involving a large portion of the posterior left atrium is more effective than pulmonary vein isolation alone.^{13,29,30} Increased left atrial size has been shown by multiple groups to be a significant risk factor for recurrence with a probability of recurrence exceeding 50% once the left atrium approaches 8 cm.^{14, 31–33} Finally early ATAs has previously been shown by

our group to be a risk factor for recurrence.¹⁴ It is likely that early ATAs are likely a marker of more advanced pathology within the atrial substrate itself and therefore it would make sense that these patients would be more likely to have a late AF recurrence.

Summary

The surgical treatment of atrial fibrillation has undergone many evolutions. The CMPIV helped to solve some of the limitations of the CMP III. With the use of ablation technology to replace the surgical incisions, similar cure rates have been achieved despite more stringent followup criteria. Because of advances in minimally invasive technologies, the CMIV operation can now be performed through a less invasive RMT approach in properly selected patients resulting in a shorter hospital stay with equivalent 2 year outcomes. As the mechanisms for AF are better understood and technology continues to improve, surgical treatments will likely become less invasive with improved cure rates as procedures are tailored to patient-specific pathology.

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Key Points

- The Cox-Maze procedure is the current gold standard in the surgical ablation of AF.
- Failure to isolate the entire posterior left atrium and the pulmonary veins greatly increases AF recurrence.
- Advances in minimally invasive techniques and technologies have allowed for a less invasive Cox-Maze procedure to be performed through a right mini-thoracotomy.

Figure 1.
Positioning for right mini-thoracotomy approach

Figure 2.

Cox-Maze IV Lesion Set as performed through a Sternotomy. **A) Right atrial lesion set** – RF ablations consist of SVC/IVC ablation and RA free wall ablation. Cryoablations include linear cryoablations through a pursestring to the 10’o clock position of the tricuspid valve annulus and through the superior aspect of the atriotomy to the 2’o clock position of tricuspid valve annulus. **B) Left atrial lesion set** – Bipolar RF ablation lines consist of bilateral pulmonary vein isolations, ablations between the left superior pulmonary vein and amputated atrial appendage, pulmonary vein roof and floor connecting ablations, and ablation between inferior aspect of the atriotomy to mitral valve annulus. Cryoablations include linear epicardial cryoablation over the coronary sinus and at the mitral valve annulus.

Figure 3.

Cox-Maze IV Lesion Set as performed through a right-ministernotomy. **A) Right atrial lesion set** – Three separate pursestrings and replacement of right atriotomy with a line of bipolar RF ablation. All other lesions are identical to the sternotomy approach. **B) Left atrial lesion set** – Left pulmonary vein isolation is achieved through sequential endocardial cryoablation and LAA is oversewn in two layers endocardially. All other lesion are identical to the sternotomy approach.