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Surgical atrial fibrillation ablation: A review of contemporary techniques and energy sources

Mehmet K. Aktas, James P. Daubert and Burr Hall

University of Rochester, Strong Memorial Hospital, Department of Cardiovascular Diseases,
Rochester, New York, USA

Introduction

Atrial fibrillation (AF) is the most common dysrhythmia, affecting an estimated 2.2 million adults in the United States, and it is projected that this number will soar to 5.6 million affected people by the year 2050 [1, 2]. Risk factors for the development of AF include advanced age, diabetes, hypertension, heart failure, valvular heart disease, coronary artery disease, left ventricular dysfunction, wide pulse pressure, excessive alcohol consumption, obstructive sleep apnea and personality traits such as anger and hostility [2–8]. Patients with uncontrolled and untreated AF are at higher risk for stroke and death and a variety of other adverse outcomes [3, 9]. In order to minimize the adverse effects of AF, considerable time, money and effort is spent in trying to maintain sinus rhythm. However, we have learned from the AFFIRM study (the Atrial Fibrillation Follow-up Investigation of Rhythm Management) that in patients with AF a treatment strategy of rhythm compared to rate control offered no mortality benefit [10, 11]. The results of the AFFIRM trial reinforced the inadequacies of achieving and maintaining normal sinus rhythm with the pharmacologic therapies that are currently available to us. Given the limitations of pharmacotherapy, alternative strategies using invasive catheter based and/or surgical ablation of AF has gained popularity.

Our understanding of the pathophysiology, the mechanisms initiating and maintaining AF, has undergone considerable change over the past 30 years. In 1998 Haissaguerre et al. [12] published a landmark paper describing focal ectopic atrial foci in the pulmonary veins that preceded paroxysmal AF (PAF), the radiofrequency ablation of which quelled the atrial foci, restoring normal sinus rhythm in some patients. Experimental studies have also demonstrated small reentrant circuits called rotors that are distributed throughout the atria forming a hierarchical distribution of frequencies [13, 14]. Catheter ablation in the anatomic area containing the dominant frequency, also known as the mother rotor, has shown reasonable success in terminating cases of PAF and chronic AF [13, 14]. Based on these pivotal studies, both catheter and surgical ablation of AF attempt to isolate the pulmonary veins from the remainder of the left atrium and target areas of fractionated atrial electrograms and dominant frequencies within the left atrium in an effort to restore and maintain normal sinus rhythm.

Several goals and benefits are desired with surgical AF ablation. The major goal of AF ablation is the restoration of atrioventricular (AV) synchrony, which often translates into hemodynamic improvements particularly in those with left ventricular dysfunction. Patients typically have less anxiety and an improved sense of well being while in normal sinus rhythm, leading to improved quality of life and exercise tolerance. Re-establishing normal bi-atrial contraction reduces the duration of stasis within the left atrium and the left atrial appendage thereby lowering the risk of cardioembolic events and occasionally obviating the need for chronic anticoagulant therapy. Ideally, one would like to achieve the aforementioned goals with minimal risk. In addition to the common risks inherent in invasive procedures, some of the described and potentially lethal complications of catheter and surgical AF ablation include atrio-oesophageal fistula

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Address for correspondence: Burr Hall, MD
University of Rochester, Strong Memorial Hospital
Department of Cardiovascular Diseases
601 Elmwood Avenue, Box 679-C
Rochester, New York 14642, USA
Tel: (585) 275 1667, fax: (585) 242 9549
e-mail: Burr_Hall@urmc.rochester.edu
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formation and myocardial ischemia or infarction as a result of injury to the left circumflex artery which runs in the atrioventricular groove usually embedded within the epicardial fat pad [15–17].

In this review, we describe the history of surgical AF ablation, review the contemporary methods and energy sources used in surgical AF treatment and describe the advantages and disadvantages of various techniques and energy sources.

Left atrial isolation

In 1980, Williams et al. [18] described a procedure called 'left atrial isolation' performed initially for the treatment of difficult to map atrial tachycardias but adapted later for the treatment of AF. The procedure confined AF to an isolated portion of the left atrium while the remainder of the heart could be activated by the sinus node. Despite restoration of sinus rhythm, ongoing anticoagulation was required for the isolated portion of the left atrium, which remained in AF. Prior to the implementation of the left atrial isolation procedure, difficult to control AF necessitated surgical His bundle ablation and permanent pacemaker placement.

In 1982, a catheter based ablation of the His bundle using catheter fulguration was described by Scheinman et al. [19], which, having undergone multiple revisions, is the basis for today's catheter based ablation of the AV node, obviating the need for surgical His bundle ablation.

Corridor procedure

In 1985, a brief abstract by Guiraudon et al. [20] described an open-heart procedure in five dogs, called the corridor procedure. The procedure was proposed as an alternative to His bundle ablation and involved isolation of the left atrial free wall followed by isolation of the sinus node from the right atrium. An area of atrial tissue was corridored to the atrial septum containing the AV node. The utility of the corridor procedure was limited by ongoing requirements for anticoagulation and the lack of AV synchrony.

Maze I, II, III procedures

Elucidation of the electrophysiological mechanism of AF and atrial flutter (AFL) and the discovery that multiple and changing patterns of reentrant circuits existed in patients with AF culminated in a surgical procedure which, in a maze-like manner, aimed to interrupt all potential circuits that could be identified by intraoperative mapping. Cox et al. [21] in 1991 described a surgical procedure now known as the Maze I procedure, which involved biatrial excisions, incisions encircling each pulmonary vein, extensive incisions starting in the right atrium and extending across the fossa ovalis, incisions from the inferior aspect of the pulmonary veins to the level of the mitral valve annulus, and finally cryoablation at –60°C within the coronary sinus.

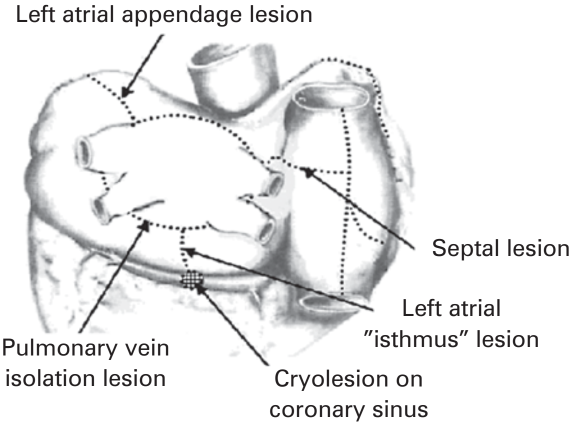

Figure 1. Standard Maze III surgical atrial fibrillation ablation. Reprinted with permission from Dr. James L. Cox, MD.

Follow-up of patients who had undergone Maze I revealed significant chronotropic incompetence and occasional left atrial dysfunction which was thought to be a result of the incisions placed near the sinus node [22]. The procedure was modified into the Maze II procedure, wherein incisions around the sinus node were not performed and several alterations where made to the left atrial incisions. This modification decreased the risk of chronotropic incompetence but at the same time introduced significant new technical challenges making it a longer and more complex surgical procedure.

Bachmann's bundle carries the sinus node impulse rapidly across from the superior septum and roof of the right atrium to the left atrium and in doing so allows near simultaneous biatrial activation and respective biventricular filling. Bachmann's bundle is either divided or incorporated into the left atrial roof incisions during the Maze I and II procedures resulting in a prolonged interatrial conduction time and AV dyssynchrony particularly between the left atrium and left ventricle [22]. For this reason, the procedure was again modified by moving the left atrial roof incisions posteriorly (Fig. 1). This apparently minor modification constituted the Maze III procedure and by doing so dramatically improved the technical and functional aspects of the procedure [22].

By July 2000 Cox [23] had reported on 308 patients who had undergone a surgical Maze III procedure with an operative mortality rate of 2.9% and a 37% incidence of post-operative arrhythmia most commonly AF and AFL. A subsequent 8½-year follow up of 178 patients who had undergone the Maze procedure showed that 93% remained arrhythmia free without anti-arrhythmic drug therapy, and the incidence of a perioperative neurologic event was only 0.7%; this is thought to be due to closure of the left atrial appendage [24].

Despite its high success rate of restoring sinus rhythm, the Maze procedures remain complex, technically challenging and require long procedure times. Ongoing research has led to the development of multiple modifications including minimally invasive approaches and alternate energy sources aimed at decreasing the length of the surgical procedure while maintaining efficacy in restoring normal sinus rhythm (Table 1).

Radiofrequency energy

Radiofrequency (RF) energy is an alternating current that generates heat by causing ions within tissue to follow the direction of the alternating current and in doing so converts electromagnetic energy to mechanical energy i.e. heat energy. In unipolar RF catheters, current flow occurs from the catheter tip to a surface grounding pad, and so there is a proportional decline in energy (heat) delivery to deeper more distal tissues. In bipolar RF catheters, current flow is between two closely opposed electrodes limiting energy (heat) flow to small volumes of myocardium. Furthermore, irrigation of RF catheters with saline serves to cool the electrode tip helping to decrease the dissipation of heat and power away from the electrode tip creating deeper and more uniform lesions. Radiofrequency energy can be applied to the endocardial and/or epicardial surfaces. Chiappini et al. [25] reported on 30 patients who had undergone a surgical Maze III procedure and 30 patients who underwent RF ablation for persistent atrial fibrillation. All of the procedures were performed by a single operator. The two groups had similar baseline characteristics and were placed on similar antiarrhythmic drug therapy (primarily amiodarone) post-operatively for up to six months following surgery. Patients were followed up for a mean of 15.5 months with the primary endpoint being the restoration of sinus rhythm [25]. The cumulative in-hospital mortality rate was not statistically different between the two groups, and the cumulative rates of sinus rhythm were 68.9% in those treated with the Maze procedure and 88.5% for those treated with RF ablation [25]. Biatrial contraction, assessed at six-month follow up, was 70.4% in those who had undergone surgical Maze and 76.5% in those treated with RF ablation [25]. Several other groups have demonstrated effective RF ablation of both paroxysmal and chronic AF when performed concomitantly during other cardiac surgeries including coronary artery bypass grafting and during valve surgery [26–28].

Microwave energy

Recent use of microwave energy has also proven to be an effective source of energy for use in catheter based surgical ablation of AF. Microwave energies include the spectrum of electromagnetic intensities ranging in frequency from 0.3 to 300 GHz. Electromagnetic radiation induced by microwave energy causes molecules to oscillate, transforming electromagnetic energy into kinetic energy and eventually thermal necrosis of myocardium. A catheter tip may have one of several different microwave antenna shapes which determine the type of

Table 1. Data obtained from references [35, 42]. Adapted from Bakir et al. [43].

Energy source	Mechanism of energy and tissue destruction	Clinical use	Endocardial/ /epicardial use
Radiofrequency	Radiofrequency current generating thermal destruction	Widely used	Both
Microwave	Electromagnetic waves generating thermal destruction	Expanding use	Both
Cryothermy	Nitrous argon resulting in ice crystal formation	Widely used	Endocardial
Ultrasound	Sound compression and rarefaction generating thermal destruction	Expanding use	Epicardial
Laser	Photons of specific wavelength generating thermal destruction	Limited	Epicardial

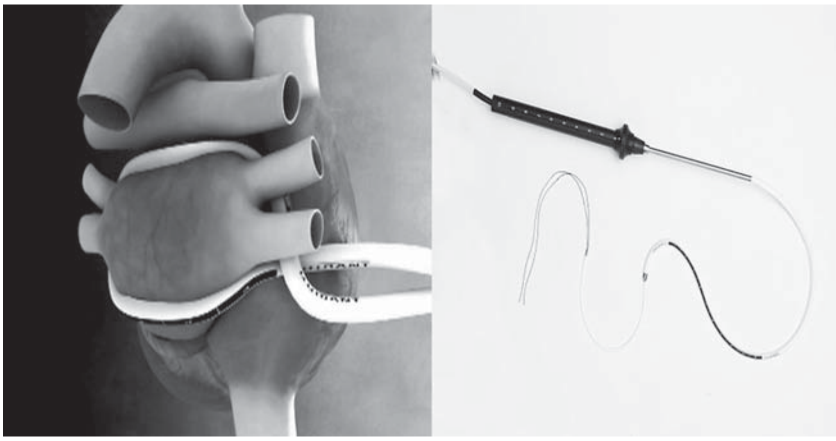

Figure 2. Microwave ablation catheter. Published with permission from Boston Scientific.

magnetic field generated (Fig. 2). In comparison to RF energy, larger and deeper lesions can be created with microwave energy. Lesion sets created during microwave energy based AF ablation are similar to RF ablation based techniques. Beating heart, minimally invasive microwave energy based catheters are now being studied as an epicardial ablation tool [29, 30]. Despite the theoretical hope of delivering transmural lesions, a postmortem analysis performed by Accord et al. [30] suggests that the created microwave lesions are highly variable and are often not transmural in nature. Gillinov et al. [31] have described the use of microwave energy for AF ablation during mitral valve surgery and Knaut et al. [32] have demonstrated the high safety and efficacy of microwave ablation of PAF during a variety of different cardiac surgeries.

Cryothermy

Cryoablation catheters have tips that can be cooled to –75°C or less, which is achieved by the infusion of nitrous argon across an area of abrupt catheter widening. In the Maze III procedure, cryothermy is an integral aspect of the procedure and is used to cryoablate within the coronary sinus. Cryoablation cools myocardium to specified temperatures with resultant intra and extracellular ice crystal formation causing irreversible cell injury and eventual necrosis (Fig. 3). The benefits of cryothermy include the preservation of the underlying cellular architecture and there is also a lower risk of char and thrombus formation. A phenomenon termed cryoadhesion, which refers to the catheter tip sticking to the myocardium during freezing, allows for stable tissue ablation. Repeated cryothermy

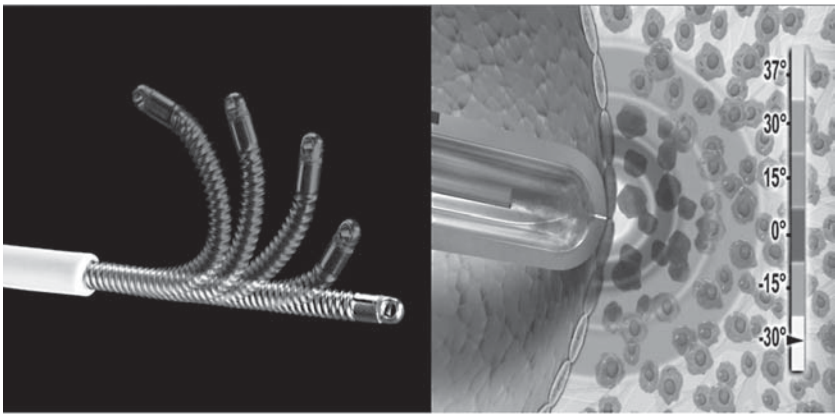

Figure 3. Argon based flexible cryoprobe by SurgiFrost Cryocath and a sample cryomap; Cryoablation device. Irvine, California. Reprinted with permission from CryoCath Technologies.

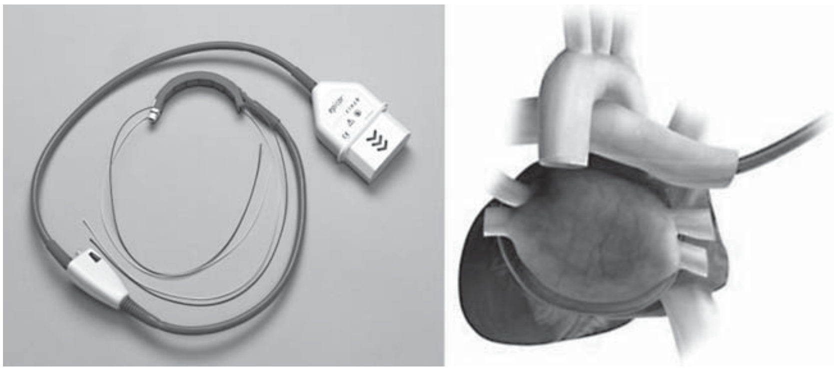

Figure 4. Epicor(tm) cardiac ablation system. High intensity focused ultrasound ablation system. Images are copyright 2007, St. Jude Medical, Inc. Reprinted with permission.

may be performed to ensure permanent cell injury. Mack et al. [33] have reported the safe and effective use of a flexible argon-based cryocatheter during concomitant cardiac surgeries. Gaita et al. [34] compared three different lesion sets in the left atrium performed with cryoablation. The lesions sets consisted of pulmonary vein isolation versus pulmonary vein isolation in addition to one or more linear ablation lines connecting the inferior pulmonary veins to the mitral annulus. When compared to cryoisolation of the pulmonary veins alone, additional linear cryoablation lesions were more effective at restoring normal sinus rhythm with a success rate as high as 85% off antiarrhythmic drugs, assuming that complete electrical block could be achieved. This study also pointed to the limitations of cryoablation because even under direct supervision, complete electrical block could only be achieved in 65% of patients with linear lesions and in 71% of patients with pulmonary vein isolation alone [34].

High frequency ultrasound energy

Sound waves propagate in a given medium mechanically, through rapidly alternating tension and compression of this medium. Sound waves with a frequency greater than 20 kHz cannot be detected by the human ear and are generally considered to be within the range of ultrasound. High intensity focused ultrasound (HIFU) typically has a much higher frequency, falling in the range of 2–20 MHz. At these far higher frequencies and with significant power, these short waves can efficiently heat tissue and while doing so can be focused to predetermined tissue depths. In general, the higher the frequency, the better the myocardium absorbs ultrasonic energy and the sharper the acoustic focusing that can be achieved (Fig. 4).

HIFU waves are created by converting electrical energy into mechanical energy, or piezocrystal vibrations, through a process called transduction and is performed by a converting device called a piezoelectric transducer. These HIFU waves can be focused, efficiently propagated and targeted towards deeper distant tissues. HIFU waves heat tissue by frictional heating producing the desired extent of thermal injury in a focal region.

An advantage of using HIFU as an ablation energy source is its ability to overcome the heat sink effect of the left atrial blood pool allowing the creation of transmural lesions when delivered from the epicardial surface. The ability to focus tissue destruction to specific depths allows for safe epicardial ablation of the left atrial isthmus, which is in close proximity to the left circumflex artery. HIFU can effectively ablate myocardium without having to dissect epicardial fat and in theory without concern for coronary artery injury. Because of the mechanics of HIFU energy deposition, and unlike thermal-gradient radiofrequency, microwave, laser or cryoablation, the amount of tissue ablated is limited to the tissue located within the base width of the transducer (ablation device).

In a prospective multicentre trial involving five European centres, off-pump epicardial HIFU ablation was used to perform single-step circumferential pulmonary vein isolation on the beating hearts of 103 patients during concomitant cardiac surgery, of whom 76 (74%) had permanent AF, 22 (21%) had paroxysmal AF and 5 (5%) had persistent AF [35]. Using a HIFU ablation device, pulmonary vein isolation was achieved in an average time of ten minutes. Using a second HIFU ablation device, an additional epicardial mitral line connecting the left pulmonary veins to the mitral annulus was performed in 34 (35%) patients. There were no reported device or ablation related complications and no deaths occurred during the trial. At six-month follow-up, freedom from AF, as measured by both surface ECG and 24-hour Holter monitoring, was 85% in the entire study group, 88% in the 35 patients who had the additional mitral line, and 100% in patients with PAF [35].

Laser

Light amplification by stimulated emission of radiation (LASER) is a beam of light with a well-defined wavelength that can be precisely focused, generating heat and tissue destruction. Using a laser energy source, surgical AF ablation has been described in a dog model. Complete pulmonary vein isolation was performed on 16 dogs and an average of 5.6 ± 0.82 lesions were performed to complete the isolation; each lesion was 45 s in duration [36]. Histochemical analysis showed all lesions to be transmural [36]. Currently there is no human data available with respect to the use of laser energy during surgical AF ablation.

Alternative energy sources *versus* Maze III

Khargi et al. [37] reviewed the efficacy of alternative energy sources (radiofrequency, microwave, cryothermy) versus the classic Maze III procedure in the surgical treatment of AF. There were 2279 patients who had undergone surgical ablation with an alternative energy source and 1153 patients who had undergone surgical Maze III. Postoperative SR rates with alternative energy sources compared to Maze III were 78.3% *vs*. 84.9% (p = 0.03) [37]. However, after controlling for type and duration of AF, and for the presence and type of concomitant cardiac surgery, the difference was no longer significant (p = 0.260) [37].

More recently, Stulak et al. [38] reported on a comparison between 56 patients who underwent surgical Cox Maze ablation using bipolar RF energy and 56 matched control patients who underwent classic cut-and-sew Cox Maze. Patients undergoing RF ablation were less likely to be free from AF at discharge (64% *vs*. 88%, p = 0.0039) and at last follow-up (62% *vs*. 92%, p = 0.016). According to multivariate analysis, patients receiving RF ablation were 4.5 times more likely to be in AF at the time of hospital discharge.

Biatrial *versus* left atrial only surgical ablation

Since its initial inception in 1987, the Cox Maze procedure has undergone numerous modifications and is the focus of ongoing research trying to identify the safest and most effective lesion sets. Barnett and Ad [39]. performed a meta-analysis comparing the safety and effectiveness of AF surgical elimination procedures involving biatrial lesions versus left atrial only lesions. Sixty-nine studies were included in the analysis, comprising 5885 patients in total with survival data reported up to three years. Patients undergoing any surgical AF ablation procedure were more likely to be free from AF (90.4–85.4%) compared to controls (47.2–60.9%). At all time points, patients undergoing biatrial lesion sets had a higher rate of freedom from AF (92.0–87.1%) compared to patients receiving left atrial only lesions (86.1–73.4%), although survival was similar [39].

Stroke rate and long-term anticoagulation following surgical Maze procedure

The stroke rate following Maze procedure is reported to be as low as 0.1% per year, due in part to the restoration of atrial transport function and atrioventricular synchrony thereby minimizing intracardiac stasis and the formation of intracardiac thrombi [40, 41]. Another contributing factor to the reduction of stroke events is the excision or ligation of the left atrial appendage during a Cox Maze procedure [41].

Use of anticoagulation following a Cox Maze procedure is in part determined by the type of concomitant cardiac surgery, if any. In a series of 306 patients, 45 required permanent anticoagulation with warfarin, and this included patients with any type of mitral prosthesis, patients with mechanical aortic valves and those in whom a Bentall procedure was performed. In this same series, 78 patients received temporary warfarin anticoagulation for a period of three months only because of a preoperative thromboembolic event, and 142 patients received no warfarin therapy at all [41]. At 11.5 years of follow up, the overall stroke rate was 0.4% [41].

Conclusions

The aim of surgical AF ablation is to achieve safe and effective arrhythmia control, potentially obviating the need for antiarrhythmic and anticoagulation therapies. Our understanding of the pathoelectrophysiology of AF has significantly improved over the past 40 years and with this new understanding we have seen the development and evolution of new surgical techniques and energy sources for ablating AF. Ongoing trials and registries will hopefully shed further light on identifying which patients need to consider surgical AF ablation, and at what point clinicians need to as well.

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