Perspective

A brief overview of surgery for atrial fibrillation

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The Maze procedure was the first surgical technique developed to ablate, rather than isolate, atrial fibrillation and was first performed clinically in 1987. The experimental and clinical electrophysiological maps on which the Maze procedure was based demonstrated the presence of two or more large (5-6 cm diameter) macro-reentrant circuits during established atrial fibrillation (AF). Eleven years later, focal triggers were identified, primarily in and around the pulmonary veins, and were shown to be responsible for the induction of individual episodes of AF. Thus, it became clear that episodes of paroxysmal AF could be treated in most patients by isolating or ablating the region of the pulmonary veins, but that once AF became non-paroxysmal and thus dependent upon the macro-reentrant circuits for its maintenance, it would still be necessary to perform some type of additional procedure to interrupt those circuits. Approximately 100,000 patients who undergo coronary artery bypass grafting (CABG), aortic valve replacement (AVR) or mitral valve surgery in the US also have associated AF, but only 20% of them undergo a concomitant procedure to ablate the AF. However, multiple studies have demonstrated that treating the AF at the time of these other primary operations results in an improved quality of life, fewer long-term strokes and improved long-term survival while adding no risk to the overall surgical procedure. Moreover, the major cardiology and surgery societies recommend that concomitant AF surgery be performed in all cases when feasible. Patients undergoing CABG and AVR who have paroxysmal AF should undergo pulmonary vein isolation, while those with non-paroxysmal AF (persistent or long-standing persistent AF) should have a Maze procedure. Patients undergoing mitral valve surgery who have either paroxysmal AF or non-paroxysmal AF should undergo a Maze procedure.

Keywords: Maze procedure; pulmonary vein isolation; concomitant atrial fibrillation; paroxysmal atrial fibrillation (PAF); non-paroxysmal atrial fibrillation (N-PAF)

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Several surgical approaches were developed in the 1980s to treat atrial fibrillation (AF), including the left atrial isolation procedure [1980] (1), the corridor procedure [1985] (2), the atrial transection procedure [1986] (3), the Maze procedure [1987] (4,5) and the radial procedure [1989] (6). The first two were designed to isolate the arrhythmia to one particular region of the atrium rather than to ablate the AF. The last three were designed to ablate the arrhythmia itself, but only the Maze procedure proved to be successful over time (7-10).

The electrophysiologic basis of AF and the Maze procedure

The Maze procedure was based not only on previous concepts introduced by Gordon Moe in the early 1960s (11,12) and confirmed by Allessie's group experimentally in the 1980s (13,14), but also on our own extensive multi-point computerized mapping of AF in experimental models and in patients with AF (15). We documented that all AF, once induced, is characterized by the presence of two or more large macro-reentrant circuits in the atria simultaneously. We then deduced that by placing atrial lesions close enough together, these large macro-reentrant circuits could not form and therefore, the atria could not fibrillate (4). We were aware that one way to accomplish this goal was to "breadloaf" the atria into small, isolated strips of tissue, but that would preclude the ability to activate the atria during any subsequent postoperative sinus rhythm. Thus,

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the dilemma was how to prevent atrial macro-reentry with surgical lesions and still leave the atria capable of resuming a normal sinus rhythm (NSR) with restoration of atrial transport function. We determined that the only method of accomplishing both goals, AF ablation and a return of NSR, was to place the lesions in the atria in the pattern of a maze, in which the lesions were close enough together to prevent atrial macro-reentry but would allow a sinus node impulse to activate the majority of both atria and to reach the ventricles via the AV node.

While we were successful in documenting the electrophysiologic characteristics of established AF (15-17), we were never able to capture the spontaneous onset of an episode of AF. It remained for Haissaguerre to demonstrate that AF episodes are induced by focal triggers in the atria, an observation that he first reported in 1998 (18). Haissaguerre noted that 90% of these triggers were located in and around the orifices of the pulmonary veins, and that the remaining 10% were located in other sites such as the right atrium, the crista terminalis, and the left atrial appendage, etc. Haissaguerre's paper resulted in an explosion of new efforts by cardiologists and surgeons worldwide to cure AF by catheter ablation and new surgical techniques, respectively. This intense activity was largely based on an over-reading of Haissaguerre's findings to mean that all one had to do to cure AF was to isolate the pulmonary veins. This oversimplification of Haissaguerre's findings resulted in the creation of an entirely new industry for the development of multiple types of ablation catheters, surgical devices and new energy sources, all of which were originally designed to isolate the pulmonary veins.

While Haissaguerre's seminal paper has resulted in millions of patients with AF receiving better care, only about 60% of all AF (paroxysmal AF) is caused by these atrial triggers. The other 40% or so of AF (non-paroxysmal AF) is due to well-established self-perpetuating macro-reentrant circuits that have little or nothing to do with these focal pulmonary vein triggers. Furthermore, the catheter mapping that was performed by Haissaguerre and by subsequent interventional electrophysiologists was performed in patients with so-called "stand-alone" AF, i.e., with AF that is not associated with other cardiac disease that is significant to warrant surgery. Since surgeons deal primarily with AF that is secondary to left heart problems such as mitral valve disease, aortic valve disease, coronary artery disease and heart failure, Haissaguerre's observation that virtually all paroxysmal atrial fibrillation (PAF) is due to pulmonary vein triggers may not be applicable in these surgical patients. No analysis of the distribution of AF triggers in the atria has been performed for patients who have so-called "concomitant AF" with which surgeons must deal. Therefore, simple pulmonary vein isolation for PAF may not be as effective in surgical patients with concomitant PAF as it is in non-surgical patients with Stand-Alone PAF.

Because of atrial remodeling (19), which often occurs after many years of PAF, the macro-reentrant circuits of AF can eventually become self-perpetuating. When this occurs, what were once only temporary episodes of AF can become long-standing or even permanent. At that point the patient has non-paroxysmal atrial fibrillation (N-PAF) and the underlying electrophysiologic culprit is no longer the focal atrial triggers but rather, the macro-reentrant circuits themselves. In these patients, simple isolation of the pulmonary veins is no longer an effective treatment because the triggers have little to do with the arrhythmia. In these patients, it is necessary to place additional linear lesions in the atria to interrupt the culprit macro-reentrant circuits. Thus, for interventional purposes, AF need be divided into only two categories: PAF and N-PAF. The universally accepted AHA/ACC/ESC classification of AF includes paroxysmal AF, persistent AF and long-standing persistent AF. However, since both persistent AF and long-standing persistent AF are dependent primarily upon macro-reentry, not atrial triggers, they should be treated the same way interventionally. In the more practical "Interventional Classification of AF", persistent AF and long-standing persistent AF are combined into the category of N-PAF.

This concept of the electrophysiology of AF has been challenged for decades, primarily by interventional electrophysiologists, and continues to be the only significant controversy surrounding the interventional treatment (catheter ablation or surgery) of AF (20). All parties agree that individual episodes of AF are induced by focal triggers as defined by Haissaguerre. However, most interventional electrophysiologists and many surgeons also believe that the mechanisms responsible for maintaining AF are focal and therefore, that even patients with N-PAF can be treated successfully by ablation of these focal sites (21-25). The one observation that ultimately refutes this concept is the fact that the Maze procedure is extremely effective in ablating AF (7-10). If N-PAF were maintained by focal abnormalities it would be impossible for the Maze procedure to work… ever! To address this obvious problem, some argue that the focal sites that supposedly maintain N-PAF are located in and around the pulmonary veins, much like the triggers that induce AF, and that they are inadvertently isolated as a part

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of the Maze procedure, explaining why the Maze procedure is effective in N-PAF. If this were the case, however, isolation of the pulmonary veins would be just as effective for N-PAF as it is for PAF and that is demonstrably not the case (26-29)!

Recently, there have been numerous publications suggesting that both PAF and N-PAF can be treated successfully by local ablation techniques if sophisticated mapping is available (24,25,30). Certainly, there are some cases in which this is true. However, the question revolves around the percentage of patients who have such focal sites that drive and maintain AF. If a significant percentage of patients had AF that was driven by these focal mechanisms, the Maze procedure would have proven to be a dismal failure rather than evolving into the so-called "gold standard" for the interventional treatment of AF (31,32). Thus, we remain convinced that all one needs to understand to treat AF successfully by interventional means is the following: (I) stand-alone PAF is caused by focal atrial triggers and can be treated satisfactorily in most patients by isolating the pulmonary veins, with the caveat that pulmonary vein isolation alone may be somewhat less successful for concomitant PAF; and (II) all N-PAF (persistent and long-standing persistent AF), whether stand-alone or concomitant, requires additional linear lesions to accompany pulmonary vein isolation in order to attain lasting results.

Why concomitant AF should be treated?

Though it is impossible to know the precise numbers involved, the best estimates are that of all the patients undergoing cardiac surgery in the U.S. each year, some 81,000 of them have a history of AF or are actually in AF at the time of surgery. Of these, only some 21,000 receive an additional surgical procedure specifically for AF in addition to their primary procedure (33). This means that the concomitant problem of AF is simply ignored in 3 out of every 4 cardiac surgical patients.

In 2010, an independent survey was conducted at the annual meeting of the American Association for Thoracic Surgery (AATS) to determine why most U.S. cardiac surgeons simply ignore the opportunity to treat AF in patients who are already going to be in their operating rooms for some other cardiac procedure (34). The overwhelming response was that surgeons were concerned that adding an AF procedure, such as pulmonary vein isolation or a Maze procedure, to the primary procedure would add too much risk. Ad and colleagues subsequently addressed this concern in a study of patients undergoing aortic valve replacement (AVR) or coronary artery bypass surgery (CABG) (35). Their conclusions were that adding a Maze procedure to the primary procedure did not increase the risk of surgery and that in fact, those patients who had the additional Maze procedures actually seemed to do better than those patients in whom AF was simply ignored.

Another concern was that surgeons who were in strictly private practices away from major medical centers might not be able to attain the same results for AF surgery that are achieved by surgeons in larger or more academic environments. Implicit in this concern was the suspicion that it simply might not matter whether or not the AF was addressed at the time of surgery for other cardiac problems. However, the surgical literature clearly documents the advantages of treating concomitant AF rather than ignoring it. Those documented advantages include enhancing the return of sinus rhythm postoperatively (36), an improved quality of life (37), less postoperative tricuspid insufficiency (38), decreasing the incidence of long-term strokes (39,40), fewer valve-related complications (40), and improved long-term survival (41).

Finally, the survey showed that surgeons seem confused in their perception that the leading societies in cardiac surgery and cardiology cannot agree on recommendations regarding how to handle concomitant AF. This is only partially true in that these societies have not yet agreed on exactly what should be done to treat the concomitant AF, i.e., which specific AF procedure to use, etc. However, the notion that these societies are unclear on whether or not concomitant AF should be treated at all is simply not accurate. A 2012 consensus statement on the surgical treatment of AF states: "*It is advisable that all patients with documented AF referred for other cardiac surgeries undergo a left or biatrial procedure for AF at an experienced center, unless it…will add significant risk…*" (42). The organizations that formed this consensus included the Heart Rhythm Society, the American College of Cardiology, the American Heart Association, the Society of Thoracic Surgeons, the European Heart Rhythm Association and the European Cardiac Arrhythmia Society. In addition, the International Society of Minimally Invasive Cardiac Surgery produced a similar statement in 2012 that reads: "*Concomitant surgical ablation is recommended…to increase the incidence of sinus rhythm both at short- and long-term follow-up… to improve ejection fraction and exercise tolerance…to reduce the risk of stroke and thromboembolic events…and to improve long-term*

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survival." (43). Thus, it is clear that the authorities in both cardiology and cardiac surgery believe that concomitant AF should be treated whenever possible.

How to treat concomitant AF

Only three groups of patients with concomitant AF will be addressed because these three groups represent the vast majority of patients who undergo cardiac surgery:

(I) Patients undergoing CABG;

(II) Patients undergoing AVR;

(III) Patients undergoing mitral valve replacement or repair.

One of the most common questions asked by surgeons is, "Are the right atrial lesions really necessary?" The literature answers this question clearly and shows that patients who undergo both right and left atrial lesions have better outcomes. Barnett and Ad performed a meta-analysis of the published literature up to 2006 that included 69 articles and 5,885 patients who had undergone either concomitant surgery or stand-alone surgery for AF (44). Their conclusion was that bi-atrial surgical procedures were more effective than left-sided procedures alone in eliminating AF. In other words, adding the right atrial lesions improved the results. The most extensive articles reporting the results of catheter ablation, surgery or hybrid procedures for the treatment of AF clearly demonstrate that the long-term results are improved by adding the right atrial lesions to the left atrial lesions (7-10,27-29).

CABG patients

Patients undergoing CABG as the primary surgical procedure but who also have AF may present with either concomitant PAF or concomitant N-PAF. Until proven otherwise, it seems prudent to treat concomitant PAF in these patients. Since inducing triggers come primarily from the region of the pulmonary veins; thus surgical isolation of the pulmonary veins is a reasonable approach. Patients with concomitant N-PAF, however, will not benefit from simple pulmonary vein isolation because the N-PAF is dependent on the self-perpetuating macro-reentrant circuits in the atrium and they must be addressed. Therefore, these patients require a Maze procedure to attain optimal results. However, the surgical dilemma here is that the Maze procedure requires opening the left atrium, and many surgeons are reluctant to add this to a standard CABG procedure that does not require a left atriotomy. Thus, the decision regarding whether or not to proceed with a full Maze procedure in these patients is left to the discretion of the surgeon. It is important to remember that adding a Maze procedure does not increase the morbidity or mortality of patients undergoing a CABG procedure (35).

AVR patients

Likewise, patients undergoing AVR as the primary surgical procedure but who also have AF may present with either concomitant PAF or concomitant N-PAF. These patients should be handled in exactly the same manner as those undergoing CABG and concomitant AF surgery. If the patient has concomitant PAF, a pulmonary vein isolation is sufficient. If the patient has concomitant N-PAF, the surgeon is faced with the same dilemma as mentioned above in regards to whether or not to open the left atrium in order to perform a full Maze procedure.

Mitral valve surgery patients

Since the left atrium has to be opened to perform mitral valve repair or replacement, all patients with either type of concomitant AF (PAF or N-PAF) should undergo a full Maze procedure.

It is worth mentioning that the most experienced arrhythmia surgeons prefer to perform a full Maze procedure for any type of AF in all patients undergoing CABG, aortic valve, or mitral valve surgery and the author supports that approach.

Surgical technique for isolating the pulmonary veins

The term "pulmonary vein isolation" can be confusing in that it refers to any one of three different procedures. The first is one in which the individual pulmonary veins are isolated. This is the type of "pulmonary vein isolation" that is done with devices like the Arctic Front catheter balloon (45,46). The second type of "pulmonary vein isolation" is one in which the right and left pulmonary veins are isolated in pairs. This is typically done when bipolar radiofrequency clamps are used (47-49). The third type of "pulmonary vein isolation" is one in which all four pulmonary veins as well as the intervening portion of the posterior LA wall are encompassed by one large encircling lesion, the so-called "box lesion". This is the type of pulmonary vein isolation that is used in all iterations of the Maze procedure (5,50,51).

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As one moves from isolating the individual pulmonary veins, to isolating them in pairs, to isolating all of them as a single unit, the results get progressively better (51).

Surgical technique for the Maze-IV procedure

Since this is not a surgical atlas; the step-by-step surgical technique of the current iteration of the Maze procedure, the Maze-IV procedure, will not be presented. However, a few pertinent points regarding surgical technique are warranted.

The left atrial portion of the Maze-IV procedure includes isolation of the pulmonary veins plus two linear lesions, a coronary sinus lesion and closure of the left atrial appendage. The two linear lesions are the so-called "mitral line" to block conduction across the left atrial isthmus between the inferior pulmonary veins and the mitral valve annulus. This mitral line in the atrial myocardium will fail to block conduction across the left atrial isthmus in approximately 15% of patients unless it is accompanied by a cryolesion in the coronary sinus in the same plane as the mitral line (1,5,50,52). The second linear lesion is placed from the left atrial appendage to the left superior pulmonary vein to preclude macro-reentry around the base of the appendage.

The right atrial lesions consist of: (I) a superior vena cava—inferior vena cava (SVC-IVC) "intercaval" lesion; (II) a "T" lesion from the intercaval lesion across the right atrial free-wall to the level of the tricuspid annulus; and (III) a "lateral right atrial lesion" from the "T" lesion to the tip of the right atrial appendage (53). These three lesions can be placed in a matter of minutes during the reperfusion/rewarming phase of the operation after the left atrial lesions have been performed under cardioplegic arrest. Thus, they do not add to the cross-clamp time, the pump time or the overall time of the operation.

The left atrial appendage

AF itself rarely kills patients; strokes due to AF kill patients. Most strokes due to AF have their origin in the trabeculated portions of the left atrial appendage (54). Oral anticoagulation therapy for the prophylaxis of strokes associated with AF is less than optimal and difficult to manage clinically (55-58). Several safe and effective percutaneous (59-61) and surgical methods (62,63) for closing the LA appendage have now been developed and will hopefully be fully approved by the FDA in the near future. These new devices and techniques have the capability of drastically reducing the number of strokes associated with AF.

The ACC/AHA Guidelines for the Management of Patients with Valvular Heart Disease recommend amputation of the LA appendage at the time of mitral valve surgery to reduce the incidence of subsequent thromboembolic events (64). Moreover, the AHA/ACC/ECS Guidelines for the Management of Patients with Atrial Fibrillation recommend surgical LA appendage closure in cardiac surgical patients "*…who are at risk of developing postoperative AF*" (65). These consensus recommendations in relatively small, highly-selected groups of patients are clearly based on recognition of the importance of the LA appendage in the genesis of strokes associated with AF. However, they beg the question of whether similar recommendations should be made to close the LA appendage in the millions of patients in the general population who have AF.

Our own experience with the surgical treatment of AF suggests that removal or proper closure of the LA appendage at the time of surgery reduces the risk of early perioperative strokes dramatically and nearly eliminates the risk of subsequent long-term stroke (66). The incidence of perioperative stroke is 3.2% following CABG, 2.8% following valve surgery and 6.7% following CABG plus valve surgery (67). However, in our experience when a Maze procedure for AF was performed either as a "stand-alone" procedure or was added to these other surgical operations as a "concomitant" procedure, the incidence of perioperative stroke dropped to less than 1% (68). This observation is particularly surprising in view of the fact that nearly 20% of the patients in our series had a history of at least one systemic thromboembolic event prior to their surgery, putting them at an even higher risk for perioperative stroke. The critical part of the Maze procedure that decreases perioperative stroke, and by inference the long-term stroke rate, is closure of the LA appendage.

The previous difficulty in attaining complete appendage closure by surgical suturing or stapling (69) has been largely overcome by the recent introduction of external clips that can be positioned quickly and easily near the base of the LA appendage during surgery. The device most commonly used is the AtriClip (Atricure, Inc., West Chester, Ohio, USA), which is designed so that the inherent expansive force exerted by the nitinol is directed centrally from both sides of the clip in order to apply a constant dynamic pressure to the base of the LA appendage, thereby keeping it closed

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permanently (63). This external clip not only closes the LA appendage effectively but it also interrupts the myocardial blood supply of the appendage itself, resulting in its gradual disappearance. In the multicenter FDA-approved EXCLUDE trial, the LA appendage was closed successfully with the AtriClip device in 98.4% of patients with no device-related mortality (63).

The LA appendage has been accurately termed "our most lethal human attachment" (70) and we are now obliged to consider its mechanical closure in a larger spectrum of the population. Certainly, the LA appendage should be closed in every patient with AF who enters our operating rooms. Indeed, it is not unreasonable to consider closing the LA appendage in all patients undergoing cardiac surgery, though a prospective, randomized trial would be essential to proving the validity of that practice.

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