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An 8½-Year Clinical Experience with Surgery for Atrial Fibrillation

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Objective

The authors analyzed the clinical results during the first 8½ years' experience with the Maze procedure for the surgical treatment of atrial fibrillation.

Summary Background Data

Atrial fibrillation occurs in 0.4% to 2% of the general population and in approximately 10% of patients older than 60 years of age. It is associated with significant morbidity and mortality. The irregular heartbeat causes discomfort, the loss of synchronous atrioventricular contraction compromises hemodynamics, and the stasis of blood flow increases the vulnerability to thromboembolism.

Methods

From September 25, 1987 to March 1, 1996, 178 patients underwent the Maze procedure. Thirty-two patients underwent the Maze-I procedure, 15 underwent the Maze-II procedure, and 118 underwent the Maze-III procedure. Patients were analyzed for recurrence of atrial flutter and atrial fibrillation between 3 months and 8½ years after surgery (n = 164). Patients were analyzed for atrial transport function, sinus nodule function, and postoperative pacemaker requirements.

Results

Ninety-three percent of all patients were arrhythmia free without any antiarrhythmic medication. Of the remaining patients with arrhythmia recurrence, all were converted to sinus rhythm with medical therapy. All patients were documented to have atrial transport function by either direct visualization, transesophageal echocardiography, or atrioventricular *versus* ventricular pacing at the same rate. Ninety-eight percent had documented right atrial function, and 94% had left atrial function. Of the 107 patients in this series who were documented to have a normal sinus node preoperatively, only 1 patient required a permanent pacemaker.

Conclusion

The Maze procedure is an effective treatment for medically refractory atrial fibrillation in properly selected patients.

Atrial fibrillation is the most common of all cardiac arrhythmias, occurring in 0.4% to 2% of the general population[1-5] and in approximately 10% of the population older than 60 years of age.[6-9] Although atrial fibrillation often is considered to be an innocuous arrhythmia, it is associated with significant morbidity and mortality because of its three detrimental sequelae: 1) an irregularly irregular heartbeat, which causes patient discomfort and anxiety; 2) loss of synchronous atrioventricular contraction, which compromises cardiac hemodynamics, resulting in varying levels of congestive heart failure; and 3) stasis of blood flow in the left atrium, which increases the vulnerability to thromboembolism.

Because medical therapy frequently fails to control atrial fibrillation, several surgical techniques have been designed either to ablate the arrhythmia or to ameliorate its attendant detrimental sequelae.[10-12] These include the left atrial isolation procedure,[10] catheter fulguration of the His bundle,[11] and the corridor procedure.[12] Each of those nonpharmacologic approaches to the treatment of atrial fibrillation provided some advantage over medical therapy, but none of them alleviated all three of the detrimental sequelae of atrial fibrillation. Because of the limitations of those surgical procedures, we initiated a series of experimental studies in 1980 with the ultimate aim of achieving a better understanding of the anatomic/electrophysiologic basis of atrial fibrillation and then developing a surgical technique to 1) cure atrial fibrillation, 2) restore atrioventricular synchrony, and 3) restore atrial transport function.

All known forms of atrial flutter and atrial fibrillation subsequently were mapped both experimentally and clinically using epicardial template electrodes and endocardial form-fitting electrodes containing as many as 256 individual bipolar contact points on the atria.[13-16] The results of our studies documented a spectrum of arrhythmias ranging from simple atrial flutter, through several types of transition arrhythmias, to complex atrial fibrillation. This entire spectrum of arrhythmias occurs as the result of macroreentrant circuits of electrical activity that require a substantial area of atrium in which to form.[17,18] When we documented that neither atrial automaticity nor atrial microreentry was involved in the genesis of these arrhythmias, the potential for surgical interruption

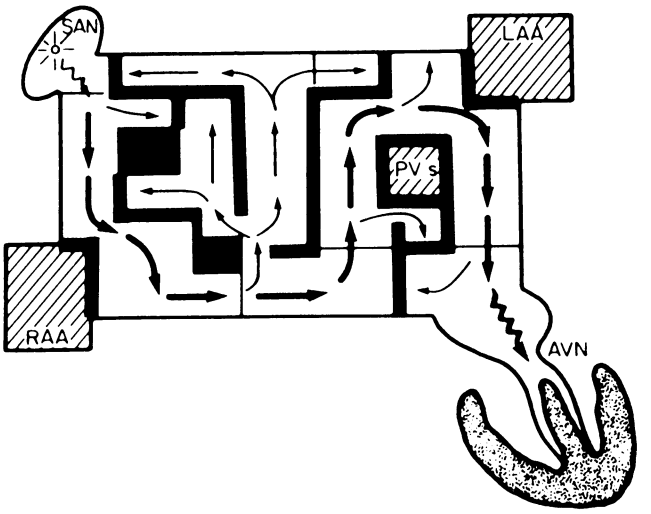

Figure 1. This two-dimensional representation of the atrial anatomy pertinent to atrial electrophysiology and the surgical treatment of atrial arrhythmias provides a conceptual diagram of the Maze procedure for the treatment of atrial fibrillation. The heavy dark lines represent atriotomies. Both the left atrial appendage and the right atrial appendage are excised, and the pulmonary veins are encircled completely. As demonstrated in this diagram, appropriately placed atrial incisions interrupt the conduction routes of the most common reentrant circuits and direct the sinus impulse from the sinoatrial node to the atrioventricular node along a specified route. The entire atrial myocardium (except for the atrial appendages and pulmonary veins) is activated electrically by providing for multiple blind alleys off the main conduction route between the sinoatrial node and the atrioventricular node, thereby preserving atrial transport function postoperatively. (From Cox et al.,[19] used with permission.)

of the larger reentrant circuits became apparent. Thus, by placing multiple strategically located transmural incisions on the atrium of specially prepared experimental animal models of atrial fibrillation, we proved that the macroreentrant circuits responsible for atrial fibrillation could be reproducibly interrupted,[19,20] thereby abolishing the ability of the atria to fibrillate. These incisions conform to the principle of a "maze" because once the atrial fibrillation has been abolished, the incisions force the electrical activity of the atria to propagate from the sinoatrial node, through one true route across the atria to the atrioventricular node, where it exits the atria on its way to the ventricles (Fig. 1).[19] This one true conduction route also is connected to multiple "blind alleys" of conduction that provide for the activation of all of the atrial myocardium, a prerequisite to restoring atrial contractile function postoperatively. Thus, the electrical activity of the atrium has one "entrance" (the sinoatrial node), one "exit" (the atrioventricular node), one true conduction route between the two, and multiple "blind alleys" of conduction, thereby conforming to the principle of a maze. It was for this reason that the surgical procedure was named the Maze procedure. This procedure has

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Table 1. INDICATIONS FOR SURGICAL INTERVENTION FOR ATRIAL FIBRILLATION

Surgical Indication	n/Total	%
Arrhythmia intolerance	118/178	66
Drug intolerance	16/178	9
Previous thromboembolism	44/178	25

been modified in several ways since its first clinical application in September 1987.[19–26] This report describes our clinical results during the first 8½ years of experience with the Maze procedure for the treatment of atrial fibrillation.

SURGICAL INDICATIONS AND CONTRAINDICATIONS

The major indication for surgery in our series has been intolerance of the arrhythmia (Table 1). Major symptoms include dyspnea on exertion, easy fatigability, lethargy, malaise, and a general sense of impending doom during the periods of atrial fibrillation.

All patients who are considered for surgery must have had unsuccessful treatment of the maximum amount of tolerable drug therapy preoperatively. In addition, approximately one fourth of the patients in our series had experienced at least one episode of cerebral thromboembolism that resulted in significant temporary or permanent neurological deficit. Documented cerebral thromboembolism in a patient with paroxysmal or chronic atrial fibrillation, in the absence of other demonstrable etiologies, is considered an absolute indication for surgery because anticoagulation does not protect such patients from a *second* stroke.[27–29] Contraindications to the Maze procedure include the presence of significant left ventricular dysfunction, not attributable to the arrhythmia itself, and concomitant cardiac or noncardiac disease that constitutes an excessive surgical risk. In addition, we have been wary of performing the Maze procedure in patients with severe hypertrophic obstructive cardiomyopathy because of the excessive risk associated with the combined procedures.

SURGICAL TECHNIQUE

The original Maze-I procedure (Fig. 2) was modified to the Maze-II procedure (Fig. 3) in an effort to improve long-term sinus node chronotropic function and to decrease postoperative interatrial conduction time that caused apparent left atrial dysfunction in a substantial number of patients.[23,25] Although the Maze-II procedure

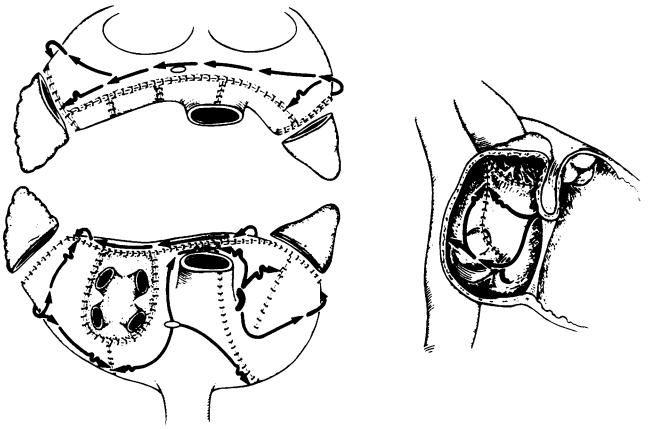

Figure 2. Location of the incisions in the Maze-I procedure. The lower panel is a posterior view of both atria. The upper panel is viewed as if the atria have been bisected in a sagittal plane and flipped upwards. The right panel is a right lateral view of the atrial septum with the right atrial free-wall cut away. Note that after the Maze-I procedure, the sinoatrial node impulse can travel in only one direction from the sinoatrial node because it cannot traverse the atriotomies. Thus, this procedure not only abolishes the reentrant circuits responsible for atrial fibrillation, but it leaves both atria capable of being activated by the sinus impulse, thereby preserving atrioventricular synchrony and atrial transport function. The short incision located just anterior to the superior vena cava orifice unfortunately traverses the so-called sinus tachycardia area, which ultimately necessitated the modification of this original procedure. (From Cox et al.,[19] used with permission.)

represented an improvement, it was an unusually difficult procedure to perform technically. As a result, it was further modified to the Maze-III procedure (Fig. 4),[23,25,26] which currently is considered to be the surgical tech-

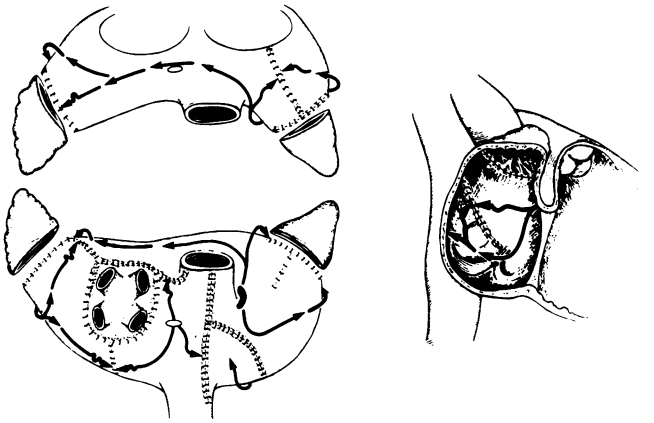

Figure 3. Maze-II procedure. Same view as in Figure 2. Note that the previous incision through the sinus tachycardia area has been deleted and the transverse atriotomy across the dome of the left atrium has been moved posteriorly to allow better intra-atrial conduction. The major problem with this modification of the maze procedure was that it was necessary to completely transect the superior vena cava to gain exposure of the left atrium. (From Cox et al.,[23] used with permission.)

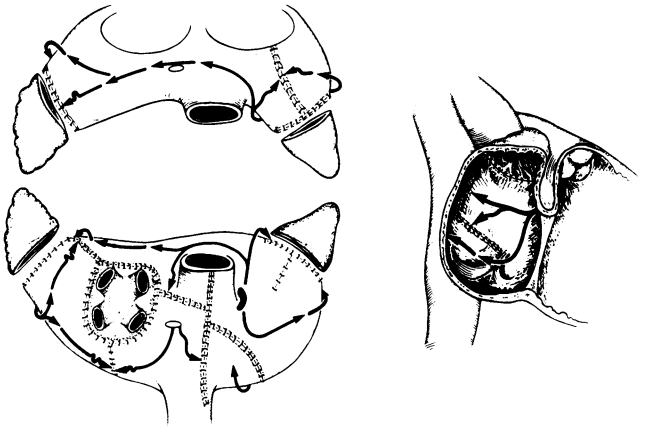

Figure 4. Maze-III procedure. Same view as in Figure 2. By placing the septal incision posterior to the orifice of the superior vena cava, the exposure of the left atrium is excellent. (From Cox et al.,[23] used with permission.)

nique of choice for the treatment of medically refractory atrial flutter and atrial fibrillation.

PREOPERATIVE PATIENT CHARACTERISTICS

Between September 25, 1987 and March 1, 1996, 178 patients underwent some variant of the Maze procedure for the treatment of atrial flutter or atrial fibrillation. Thirty-two of the first 33 patients underwent the standard Maze-I procedure, the next 15 patients had the Maze-II procedure, and the remaining 117 patients underwent the Maze-III procedure. Patient 2 underwent the equivalent of the Maze-III procedure and is included in that group, for a total of 118 Maze-III patients.

There were 131 men and 47 women with an average age of 54 years (range, 22–77 years). The preoperative arrhythmia was paroxysmal (intermittent) in 103 of 178 patients (58%) and chronic (continuous) in 75 of 178 patients (42%). The average duration of the arrhythmia preoperatively was 9 years in the paroxysmal group and 11 years in the chronic group. Thirteen patients had undergone previous cardiac surgery so that the Maze procedure was performed as a reoperative surgical procedure (Table 2). Fifty-nine patients (33%) underwent some type of concomitant cardiac surgical procedure in addition to the Maze procedure for atrial fibrillation (Table 3).

EARLY SURGICAL RESULTS: LESS THAN 3 MONTHS AFTER SURGERY

Four of 178 patients (2.2%) died in the perioperative period, the first after the Maze-II procedure combined with a Morrow myotomy and myectomy for end-stage hypertrophic obstructive cardiomyopathy. Three deaths followed the Maze-III procedure; the first was a 72-year-old coal miner with black lung disease taking amiodarone who died of postoperative respiratory insufficiency; the second was a 72-year-old man who had an unexpected cardiac arrest due to delayed cardiac tamponade; and the third was a 77-year-old woman taking amiodarone who died of severe early postoperative respiratory insufficiency. There has been one late sudden death—*i.e.*, a 61 year-old man 4 years after undergoing the Maze-I procedure.

Table 2. TYPES OF SURGERY THAT 13 OF THE PATIENTS HAD UNDERGONE BEFORE THE MAZE PROCEDURE WAS PERFORMED*

Previous Surgery	n
Mitral valve surgery	5
Atrial septal defect closure	3
Coronary artery bypass grafting	3
Aortic valve replacement	2
Tricuspid valve surgery	1
WPW and AVNRT correction	1
Atrial transection procedure	1

WPW = Wolff-Parkinson-White syndrome; AVNRT = atrioventricular node reentry tachycardia.
* Some of the patients had more than one of these procedures.

Table 3. CONCOMITANT SURGICAL PROCEDURES PERFORMED ALONG WITH THE MAZE PROCEDURE IN 59 PATIENTS*

Concomitant Surgical Procedure	n
Coronary artery bypass grafting	25
Mitral valve repair	15
Mitral valve replacement (first-time)	2
Mitral valve replacement (redo)	4
Closure of secundrum ASD	6
Closure of sinus venosus ASD with anomalous PVR	1
Tricuspid valve repair	1
Morrow procedure	1
Anomalous coronary artery repair	1
Atrial septal aneurysm repair	1
Ventricular septal aneurysm repair and redo CABG	1
Left atrial myxoma resection	1

* Some of the patients had more than one of these procedures performed. For example, one 74-year-old man had a redo quadruple CABG procedure plus a mitral valve repair plus a Maze procedure.
CABG = coronary artery bypass grafting; ASD = atrial septal defect; PVR = pulmonary venous return.

The most common complications after all three variations of the Maze procedure were perioperative atrial arrhythmias and early postoperative fluid retention. The perioperative arrhythmias are treated in the same manner as those occurring after any type of cardiac surgery and they do not have any relationship to the ultimate success of the surgical procedure. The postoperative fluid retention also is transient and is treated with spironolactone prophylactically and aggressive diuretic therapy as needed.

Patients are not anticoagulated routinely unless they have a history of thromboembolism. Only one perioperative stroke occurred (Maze-I) and it completely resolved within several weeks. There were two additional transient ischemic attacks and one perioperative myocardial infarction.

LATE SURGICAL RESULTS: 3 MONTHS TO 81/2 YEARS AFTER SURGERY

As of March 1, 1996, 164 of the 178 patients had been followed at least 3 months postoperatively (i.e., they had recovered from surgery). These "late results" were tabulated in those 164 patients. There have been only two late transient ischemic attacks, and there have been no late strokes related to the surgical procedures, to the occasional short-term postoperative anticoagulation, or to recurrent atrial arrhythmias. One patient not treated with anticoagulants had a hemorrhagic stroke 38 months after surgery, due to long-standing, severe hypertension that was present preoperatively.

Postoperative Sinoatrial Node Function

The different types of Maze procedures substantially had different effects on late function of the sinoatrial node. The incidence of inappropriate resting sinus tachycardia increased with the Maze-III procedure. This phenomenon occurred between 4 and 12 months postoperatively and was characterized by an average resting heart rate of 120 beats per minute. All 15 patients with this problem were treated successfully with low-dose oral beta-blockers.

Deletion of the Maze-I incision through the "sinus tachycardia region" of the atrial pacemaker complex resulted in an improvement in the ability of the sinoatrial node to generate an appropriate sinus tachycardia postoperatively.[25] The average maximal heart rate with exercise postoperatively was 116 ± 15 bpm after the Maze-I procedure, 132 ± 14 bpm after the Maze-II procedure, and 139 ± 19 bpm after the Maze-III procedure ($p < 0.05$, comparing Maze-II to Maze-I; $p < 0.001$ comparing Maze-III to Maze-I).

Table 4. DIRECT RESULTS OF MAZE PROCEDURE ON SINUS NODE FUNCTION

Procedure	Preoperative Normal SA Node (n)	Postoperative Pacemaker (n)	%
Maze-I	15	1	6
Maze-II	10	0	0
Maze-III	82	0	0
Total	107	1	1

* Of the 164 patients followed long-term (*i.e.*, from 3 months to 8.5 years after surgery), 107 were documented to have normal sinoatrial (SA) nodes preoperatively. Only 1 of those 107 patients had to have a permanent pacemaker postoperatively, that being the third patient in the series. These values confirm that the Maze procedure itself, regardless of the type employed, is not responsible for the 25–30% incidence of pacemaker requirements postoperatively.

Postoperative Pacemaker Requirements

Of the 107 patients in this series who were documented to have normal sinoatrial nodes preoperatively, only 1 patient required a permanent pacemaker postoperatively (1%; Table 4). This observation emphasizes the fact that the Maze procedure itself is not the reason that patients need pacemakers postoperatively. Preoperative Sick Sinus Syndrome was present in 29 patients preoperatively (18%), and 19 additional patients (12%) already had permanent pacemakers implanted before surgery. One patient required a permanent pacemaker postoperatively because of inadvertent heart block caused by extensive surgery in the posterior septal space to reroute an anomalous coronary sinus into the right atrium. Thus, a total of 50 of the 164 patients (30%) have permanent pacemakers postoperatively, although only one can be attributed to the adverse effects of the Maze (I) procedure. Interestingly, the requirements for permanent pacemakers decreased substantially during the surgical evolution from the Maze-I procedure (56%) to the Maze-II procedure (29%) to the Maze-III procedure (24%), probably because of fortuitous and unintended patient selection.

Postoperative Arrhythmia Recurrence

Recurrent atrial flutter developed in six patients, after the Maze-I procedure in four patients and after the Maze-II procedure in two. All six patients were treated successfully with a single antiarrhythmic drug. Six other patients experienced recurrent atrial fibrillation, 2 of 32 patients after the Maze-I procedure (6%), 1 of 14 after the Maze-II procedure (7%), and 3 of 121 after the Maze-III procedure (2%). All six patients converted to sinus

Table 5. RECURRENCE OF ATRIAL FLUTTER AND ATRIAL FIBRILLATION BETWEEN 3 MONTHS AND 8.5 YEARS AFTER SURGERY

Procedure	n	Recurrent A-Flutter	Recurrent AFib	Total Recurrences	% Recurrences
Maze-I	32	4	2	6	19
Maze-II	14	2	1	3	20
Maze-III	118	0	3	3	2
Total	164	6	6	12	7

rhythm with medical therapy. Thus, as of March 1, 1996, there was a combined recurrence rate of atrial flutter or atrial fibrillation for all variations of the Maze procedure of only 12 of 164 patients (7%) (Table 5), all of whom were converted successfully to sinus rhythm with medical therapy. The other 93% of patients were free of arrhythmias without any antiarrhythmic medication.

Postoperative Atrial Function

Immediately after completing the surgical procedure, both left and right atrial transport function were evaluated in all patients by direct visualization, transesophageal echocardiography, or atrioventricular pacing *versus* ventricular pacing at the same paced rates. In addition, most patients underwent either dynamic or three-dimensional magnetic resonance imaging or transthoracic echocardiography at least once before hospital discharge. It was assumed that any of these tests could give a false-negative result, but not a false-positive result. Therefore, if any one of these tests indicated the presence of atrial mechanical contraction, atrial transport function was considered to be present in that atrium, regardless of the results of the remaining tests. By one or more of these techniques, all patients were documented to have both right and left atrial transport function in the early postoperative period.

Table 6. PRESERVATION OR RESTORATION OF ATRIAL TRANSPORT FUNCTION IN EACH ATRIUM FOLLOWING THE MAZE PROCEDURE*

Procedure	Preserved Postoperative Right Atrial Function	Preserved Postoperative Left Atrial Function
Maze-I	32/32 (100%)	23/32 (72%)
Maze II	11/11 (100%)	7/11 (64%)
Maze-III	80/82 (98%)	77/82 (94%)
Total	123/125 (98%)	107/125 (86%)

*The tests for atrial function were performed at least 6 months after surgery.

Table 7. COMPARISON OF THE EFFECTS OF THE THREE DIFFERENT TYPES OF MAZE PROCEDURES ON SEVERAL LONG-TERM POSTOPERATIVE PARAMETERS*

Postoperative Parameter	Maze-I (%)	Maze-II (%)	Maze-III (%)
Blunted SA node chronotropy	88	21	6
Iatrogenic SA node injury	6	0	0
Pacemaker requirement	56	29	24
Atrial flutter recurrence	13	14	0
Atrial fibrillation recurrence	6	7	2
Dysfunctional left atrium	28	36	6

* Note that the Maze-III modification has resulted in substantial improvement in all of these parameters.

As of March 1, 1996, 125 patients had been re-evaluated approximately 6 months after surgery specifically for the presence or absence of right atrial, left atrial, and overall atrial transport function. These evaluations included all of the same tests performed perioperatively, except direct visualization, and the same criteria for positive results were used. The presence of right atrial and left atrial function, respectively, after the three types of Maze procedures is listed in Table 7. After the Maze-III procedure, right atrial function is preserved in 97% of patients and left atrial function is preserved in 94% of patients. Thus, not only is the atrial fibrillation abolished, but also the sinus rhythm (or atrial pacing) that is restored results in functional atrial contractions.

Thus, the three objectives of our surgical approach to the treatment of atrial fibrillation have been met satisfactorily because with the current technique, the cure rate is 100%, the restoration of atrioventricular synchrony is 100%, and the preservation of atrial transport function is 98% in the right atrium and 94% in the left atrium. We believe that these results warrant the continued application of the Maze-III procedure for the treatment of medically refractory atrial fibrillation in properly selected patients.

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Discussion

DR. ALDEN H. HARKEN (Denver, Colorado): It really is a privilege to watch these kinds of studies evolve. I would suggest, Dr. Wells, that this is a beautiful preemptive example of your Presidential Address, "The Surgical Sciences." Dr. Cox has taken a very common and debilitating clinical problem, taken it to the laboratory, solved it in the laboratory, then applied it to patients, and then perhaps equally important, promoted, stimulated, and encouraged the application of this therapy in other clinics such as our own. I have two questions.

Dr. Cox, you allude to atrial fibrillation causing two objective and one subjective problems. The two objective problems are thromboembolism and atrial transport function. The thromboembolic problem is a very real one with atrial fibrillation. However, you filet the atrium into multiple channels, thus detouring an impulse from the SA node down to the atrioventricular node, and incise that atrium down into these channels that are simply electroanatomically incapable of sustaining a re-entrant rhythm. You indicated it was pretty easy to cut the atrium up like that and indeed it is. Putting it back together again is a little bit more daunting. In fact, as a surgeon, you look down and it looks like a lawn mower accident. But you have all of these suture lines. Do you have either microscopic or macroscopic evidence of the relationship between the thromboembolic process and those suture lines at days, weeks, months or years?

The second question concerns the atrial transport function. When we looked at atrial transport with atrial fibrillation in patients relative to their ventricular function, folks with good