Wiley
Journal of Cardiac Surgery
Volume 2024, Article ID 1136595, 9 pages
https://doi.org/10.1155/2024/1136595

WILEY

Research Article

Single-Center Success of Concomitant Cryothermal Cox-Maze IV Procedure

Benedikt Mayr,[1] **Anna Maria Kokott**,[1] **Teodora Georgescu**,[1] **Bernhard Voss**,[1] **Markus Krane**,[1,2,3] **and Keti Vitanova**[1]

[1]*Department of Cardiovascular Surgery, Institute Insure, German Heart Center Munich, School of Medicine and Health, Technical University of Munich, Munich, Germany*
[2]*Division of Cardiac Surgery, Department of Surgery, Yale School of Medicine, New Haven, USA*
[3]*DZHK (German Center for Cardiovascular Research)-Partner Site Munich Heart Alliance, Munich, Germany*

Correspondence should be addressed to Markus Krane; krane@dhm.mhn.de and Keti Vitanova; vitanova@dhm.mhn.de

Received 20 March 2024; Revised 7 August 2024; Accepted 17 August 2024

Academic Editor: Piotr Mazur

Background. Despite the guideline recommendation, implementation of the Cox-maze (CM) IV procedure has been variable and current data are limited. *Methods*. We reviewed patients with concomitant CM IV procedure (05/2019–05/2020). The primary endpoints of the study were the success rate of surgical ablation and continuity of sinus rhythm (SR) 1 year after surgery. Secondary endpoints included permanent pacemaker (PPM) implantation, postoperative mortality, and identification of predictors for postoperative SR. *Results*. The concomitant CM IV procedure was performed in 92 patients. Indications were persistent atrial fibrillation (AF) in 40 patients (43.5%), paroxysmal AF in 36 (39.1%), and long-standing persistent AF in 16 (17.4%). At hospital discharge, SR was achieved in 49 patients (63.6%) and PPM implantation was necessary in 12 patients (13%). At 1 year after surgical ablation, SR was seen in 31 patients (59.6%) and PPM implantation was required in six further patients (6.5%). Patients with long-standing persistent AF were significantly less likely to achieve SR (odds ratio (OR): 0.18, $p = 0.003$), and postoperative mortality was significantly increased in this subgroup (hazard ratio (HR): 5.4, $p = 0.02$). In patients with enlarged left atrial (LA) diameter, the probability of achieving SR was significantly decreased (OR: 0.48, $p = 0.045$). Need for postoperative dialysis (HR: 12.9, $p = 0.02$) and prolonged stay in the intensive care unit (HR: 2.2, $p = 0.01$) were independently associated with increased mortality after CM IV. *Conclusions*. The cryothermal CM IV procedure has an overall 1-year success rate of 60% with increased rates of PPM implantation. Patients with long-standing persistent AF and increased LA diameter were significantly less likely to achieve SR.

1. Introduction

Atrial fibrillation (AF) is the most common cardiac arrhythmia worldwide with an estimated prevalence of 1.5–2% [1, 2]. The prevalence of AF is increasing nowadays due to the improved detection of AF, the higher life expectancy of the population, and the increased corresponding comorbidities predisposing to the development of AF [3]. The risk for stroke, left ventricular dysfunction, and overall mortality is four to five times increased in patients with AF [4–6]. Surgical ablation for AF should be considered in patients undergoing cardiac surgery and is recommended at the time of concomitant valve surgery and coronary artery bypass grafting by the European (Class IIa, Level A) [4] and American guidelines (Class I, Level B) [7]. The state-of-the-art surgical ablation technique is the Cox-maze (CM) procedure, which was first performed by James Cox in 1987 [8]. The currently used form of the CM is the CM IV in which multiple surgical incisions in the left and right atria (cut-and-sew technique, CM III) were replaced by a combination of bipolar radiofrequency and cryothermal energy facilitating transmural and continuous ablation lines [9]. The stand-alone CM IV procedure is associated with freedom from AF rates at 3, 6, and 12 months postsurgical ablation of

93%, 90%, and 90% [10]. Atrial fibrillation is often coincident with other heart valve diseases such as mitral valve (MV) disease, and the addition of surgical ablation in patients with long-standing AF undergoing MV surgery increased the number of patients who were free of AF 1 year following surgery (63.2%) [11]. However, patients with longer preoperative AF duration and older age were at increased risk of late-onset permanent pacemaker (PPM) implantation [12]. An important factor for the possible recurrence of AF after surgery is the size of the left atrium (LA). Damiano et al. described a greater than 50% probability of recurrence of AF after surgical ablation when the LA diameter was more than 8 centimeter [13].

The aim of our study was to evaluate the success rate of cryothermal CM IV with attention to the preoperative type of AF and to identify predictors for postoperative sinus rhythm (SR).

2. Materials and Methods

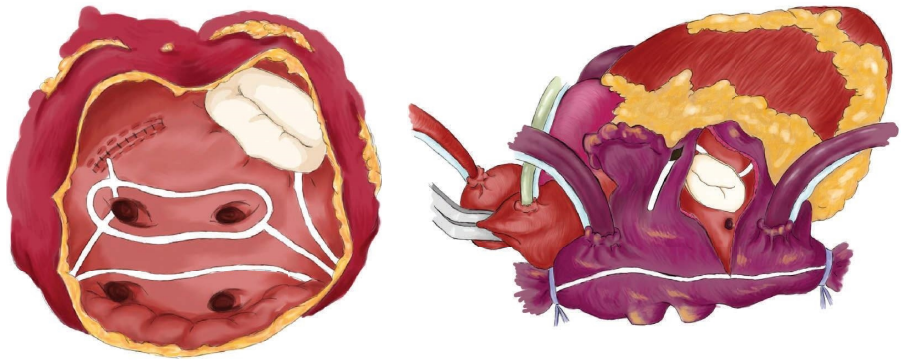
2.1. Study Design and Study Population. The Institutional Review Board of the Technical University of Munich approved the retrospective study (ID: 2022-553-S-KH, Date: 31.10.2022), and the need for informed patient consent was waived. Patients with concomitant CM IV procedure using cryothermal energy, operated on between May 2019 and May 2020, were included in our study. Patients with epicardial pulmonary vein isolation and preoperative PPM implantation were excluded from the analysis. All CM IV procedures were performed concomitantly. The main surgical procedures were mitral and tricuspid valve repair, and mitral valve replacement. Atrial fibrillation was defined as paroxysmal, persistent, or long-standing persistent per recent guidelines [14]. Other arrhythmias (OA) included atrial flutter and complex supraventricular arrhythmias. Preoperative evaluation of the left ventricular and LA dimensions, as well as the function of the left ventricle, was performed by transthoracic echocardiography [15]. In all patients, ablation lines were performed using the Medtronic Cardioblate CryoFlex system (Medtronic, Inc., Minneapolis, MN, USA). Left atrial ablation lines were performed with the cryoprobe placed on the endocardium and cooled to −150°C for 2 minutes. Right atrial ablation lines were performed with the cryoprobe cooled to −150°C for 1.5 minutes.

2.2. Surgical Technique. After median sternotomy and cardioplegic arrest, the heart was retracted and the left atrial appendage (LAA) was exposed and either amputated or occluded using suture according to European (Class IIb, Level C) [4] and American guidelines (Class IIa, Level C) [7]. In patients with difficult exposure of the LAA and deep thoracic cavity, LAA occlusion was facilitated by the use of AtriClip (AtriCure, Inc., OH, USA). Via the amputated LAA, a connecting ablation line was created to the left superior pulmonary vein. Closure of the LAA was achieved by two layers of felt strip with a running polypropylene suture. After the dissection of the interatrial groove, the left atrium was opened in a standard fashion and an ablation line was created along the inferior margin of the right pulmonary veins (PVs) completing the first box lesion. The second box lesion of the left PV was created with a line along the superior margin of the left PV and a line along the inferior margin of the left PV. The PV box lesions were connected with two ablation lines reaching from the right to the left inferior and superior PVs. The next left atrial lesion was an ablation line from the right inferior PV down to the posterior portion of the mitral annulus followed by an epicardial ablation on the coronary sinus. All right atrial lesions were performed on the beating heart, and an oblique right atriotomy was made. The first right atrial ablation line was created reaching from the superior vena cava down towards the inferior vena cava. The second and third right atrial ablation lines reached from the atriotomy down to the tricuspid annulus at the 10 and 2 o'clock positions. The details of the operative technique are depicted in Figure 1.

2.3. Antiarrhythmic and Anticoagulation Management. For early postoperative rhythm and rate control, beta-blockers ($n = 77$, 84%) and amiodarone ($n = 15$, 16.3%) were initiated and discontinued at 3 months after surgery if SR prevailed. After surgery, all patients were anticoagulated with phenprocoumon. Phenprocoumon was discontinued at 3 months if patients were free of AF or OA.

2.4. Follow-Up Data. Follow-up data and death were acquired from medical charts, cardiologists, and phone calls. At discharge, a 12-lead electrocardiogram (ECG) and transthoracic echocardiography were performed. At 3, 6, and 12 months after surgery, a 24-hour ECG was performed at the Department of Cardiology of the German Heart Center Munich. If the patient was not able to get the 24-hour ECG at the Department of Cardiology due to COVID-19 restrictions or other circumstances, the patient's cardiologist was contacted for further information about possible 12-lead or 24-hour ECG and PPM interrogation.

2.5. Statistical Analysis. Data analysis was performed using the IBM Statistical Package for the Social Sciences, version 28.0 for Windows (IBM Corp., Armonk, NY, USA). Descriptive statistics are described as frequencies and percentages for categorical variables. Continuous variables are reported as mean ± standard deviation if normally distributed and as median with interquartile ranges (IQRs) if non-normally distributed. The normality of continuous variables was tested with the Kolmogorov–Smirnov test, histograms, and P-P plots for graphical testing. The Kaplan–Meier analysis was applied to estimate survival. The log-rank test was used to compare survival between the groups. Riverplots were used for visualization of the heart rhythm variability postmaze during the follow-up. A comparison of postoperative rates of SR, AF, PPM, and OA between patients with paroxysmal, persistent, or long-standing persistent AF was made using the analysis of variance. In the case of inhomogeneity of variance, the Games–Howell test was used for post hoc analysis. Factors for SR after CM IV were



(a) (b)

Figure 1: Details on the operative technique of the biatrial cryothermal Cox-maze IV procedure.

identified using a logistic regression model. Risk factors for mortality after CM IV were identified using a Cox regression analysis. For multivariable analysis, we used the Cox proportional hazards regression method to identify the variables that were independently predictive of events. Hazard ratios with 95% confidence intervals were estimated. Final models were derived by the forward and backward stepwise selection procedure. Variables with a level of significance of less than 0.1 in the univariable analysis were entered into the Cox and multiple logistic regression models. p values <0.05 were considered significant.

3. Results

3.1. Patient Characteristics. During the study period, 92 consecutive patients underwent the concomitant CM IV procedure. Indication for surgical ablation was persistent AF in 40 patients (43.5%), paroxysmal AF in 36 patients (39.1%), and long-standing persistent AF in 16 patients (17.4%). Preoperative interventions such as electrical cardioversion and catheter ablation had been performed in 44 (47.8%) and 16 (17.4%) patients, respectively. Previous cardiac surgery had been performed in 13 patients (14.1%). Before surgical ablation, 83 patients (90.2%) were fully anticoagulated and antiarrhythmic drugs included beta-blockers in 71 patients (77.2%) and amiodarone in 11 patients (12%). At the time of surgery, left atrial (LA) dimensions were enlarged (mean LA diameter: 5.1 ± 1 cm; mean LA volume index: 65.8 ± 25.4 ml/m^2). The mean age at the time of surgery was 70.7 ± 7.9 years. The exclusion of the left atrial appendage (LAA) was performed in 91 patients (98.9%). In one patient, LAA exclusion via suture was technically not possible due to extensive adhesions of the LAA to the left upper pulmonary vein. Further details on baseline and perioperative characteristics are listed in Tables 1 and 2. A detailed summary of all surgical procedures and concomitant Cox-maze IV is depicted in Supplemental Table 1.

3.2. In-Hospital Outcome. In-hospital mortality was 4.3% ($n = 4$). The causes of death were sepsis-induced multiple organ failure ($n = 2$), mesenteric ischemia ($n = 1$), and pulmonary insufficiency ($n = 1$). Postoperative stroke was seen in two patients (2.2%), and dialysis was required in 10 (10.9%). In 12 patients (13%), PPM was implanted at a median of 10 (IQR, 4.8–13.5) days after surgery. A detailed overview of postoperative PPM implantation is depicted in Table 3. At hospital discharge, in patients without PPM implantation, SR was achieved in 49 patients (63.6%) and AF persisted in 28 patients (36.4%).

3.3. Follow-Up Outcome. The mean follow-up time was 13.3 ± 5.6 months with a late mortality of 5.4% ($n = 5$). Follow-up at 3, 6, and 12 months after surgery was obtained in 52 (56.5%), 53 (57.6%), and 52 patients (56.5%), respectively. The complete consecutive follow-up information at 3, 6, and 12 months was achieved in 32 patients (34.7%). In three patients (3.2%), no follow-up information was available at any time point during follow-up. At 3 months, SR was seen in 33 patients (63.5%) and AF in 15 patients (28.9%) (Figure 2). In three patients (5.8%), catheter ablation due to persisting AF was performed at 4, 4.8, and 4.9 months after CM IV. At 6 months after the CM IV procedure, SR was detected in 33 patients (62.3%) and AF in 13 patients (24.5%). Catheter ablation was necessary in three patients at 5.3, 7.4, and 9.5 months after CM IV. At 12 months after surgery, SR was seen in 31 patients (59.6%), AF in 16 (30.8%), and OA in 5 (9.6%). Variability of SR and AF during the 12-month follow-up is depicted in Figures 3 and 4, respectively. Patients with 3- and/or 6-month follow-up were summarized in one group. If AF or OA occurred either 3 or 6 months after maze, the patient was added to the group AF/OA. If no follow-up was available at 3 and 6 months after surgery, the patient was added to the group no follow-up. One-year survival after surgical ablation was 89.8 ± 3.2% (Supplemental Figure 1) with significantly decreased survival in patients with long-standing persistent AF (94.5 ± 2.7% vs. 68.2 ± 11.8%, $p = 0.001$) (Supplemental Figure 2).

At the last follow-up, SR was seen in 50 patients (54%) and Games–Howell post hoc analysis showed that SR was significantly more often achieved in patients with

Table 1: Baseline characteristics.

Variable	All patients ($n = 92$)	Patients with paroxysmal AF ($n = 36$)	Patients with persistent AF ($n = 40$)	Patients with long-standing persistent AF ($n = 16$)
Gender, female	33 (35.9)	12 (33.3)	15 (37.5)	6 (37.5)
Age (years)	70.69 ± 7.88	69.26 ± 8.55	71.46 ± 7.21	71.96 ± 7.92
BMI (kg/m^2)	27.8 ± 6.9	27.1 ± 5.3	28.3 ± 8.3	27.9 ± 6.4
Preoperative medication				
Anticoagulation	83 (90.2)	29 (80.6)	39 (97.5)	15 (93.8)
Beta-blocker	71 (77.2)	25 (69.4)	32 (80)	14 (87.5)
Amiodarone	11 (12.0)	1 (5.6)	8 (20)	2 (12.5)
Preoperative intervention				
Electric cardioversion	44 (47.8)	12 (33.3)	26 (65)	6 (37.5)
Catheter ablation	16 (17.4)	2 (5.6)	13 (32.5)	1 (6.3)
Preoperative ICD	3 (3.3)	1 (2.8)	1 (2.5)	1 (6.3)
Comorbidities				
Coronary artery disease	20 (21.7)	7 (19.4)	10 (25)	3 (18.8)
Diabetes mellitus	7 (7.6)	1 (2.8)	3 (7.5)	3 (18.8)
Renal disease	18 (19.6)	7 (19.4)	9 (22.5)	2 (12.5)
Pulmonary disease	39 (42.4)	11 (30.6)	17 (42.5)	11 (68.8)
Cerebrovascular disease	17 (18.5)	8 (22.2)	6 (15)	3 (18.8)
Previous cardiac surgery	13 (14.1)	4 (11.1)	6 (15)	3 (18.8)
Valve pathology				
MV regurgitation degenerative	51 (55.4)	19 (52.8)	22 (55)	10 (62.5)
MV regurgitation functional	34 (37.0)	13 (36.1)	15 (37.5)	6 (37.5)
MV stenosis	5 (5.4)	2 (5.6)	0	3 (18.8)
TV regurgitation	55 (59.8)	20 (55.6)	23 (57.5)	12 (75)
AV regurgitation	13 (14.1)	5 (13.9)	5 (12.5)	3 (18.8)
AV stenosis	7 (7.6)	1 (2.8)	5 (12.5)	1 (6.3)
Preop. LA diameter (cm)	5.14 ± 1.04	4.9 ± 0.87	5.05 ± 0.66	6.2 ± 1.88
Preop. LAVI (ml/m^2)	65.84 ± 25.38	70.18 ± 30.96	58.23 ± 14.79	71.98 ± 28.73
Preop. LVEDD (cm)	5.51 ± 1.17	5.52 ± 1.43	5.53 ± 0.98	5.43 ± 0.92
Preop. LVEF (%)	52.27 ± 11.41	54.68 ± 11.21	50.69 ± 10.85	50.36 ± 12.96

Values are expressed as n (%) or mean ± standard deviation. AF: atrial fibrillation, AV: aortic valve, ICD: implantable cardioverter-defibrillator, LA: left atrial, LAVI: left atrial volume index, LVEDD: left ventricular end-diastolic diameter, LVEF: left ventricular ejection fraction, MV: mitral valve, preop: preoperative, TV: tricuspid valve, and BMI: body mass index.

Table 2: Peri- and intraoperative details.

Concomitant procedures	
Mitral valve repair	55 (59.8)
Mitral valve replacement	20 (21.7)
Tricuspid valve repair	55 (59.8)
Aortic valve replacement	18 (19.6)
Aortic valve repair	2 (2.2)
CABG	20 (21.7)
LAA amputation	81 (88)
LAA occlusion suture	6 (6.5)
LAA occlusion clip	4 (4.3)
AXC time (min)	111.1 ± 33.21
CPB time (min)	157.93 ± 43.35
ICU stay (days)	4 (1–98)
Hospital stay (days)	13 (6–175)
Postop. use of beta-blockers	77 (84.0)
Postop. use of amiodarone	15 (16.3)

Values are expressed as n (%) or median (interquartile range). AXC: aortic cross-clamp, CABG: coronary artery bypass grafting, CPB: cardiopulmonary bypass, ICU: intensive care unit, LAA: left atrial appendage, Postop: postoperative.

paroxysmal than long-standing persistent AF (0.56, 95% CI: 0.26–0.87, $p < 0.001$) (Supplemental Figure 3). Postoperative SR was more frequently achieved in patients with persistent than long-standing persistent AF ($p = 0.05$). Atrial fibrillation was detected in 27 patients (29.3%) at the last follow-up with no statistical difference between the preoperative AF groups ($p = 0.05$) (Supplemental Figure 3).

3.4. Risk Factor Analysis for Sinus Rhythm and Mortality after Cox-Maze IV. By univariate analysis, patients with preoperative long-standing persistent AF were significantly less likely to achieve SR after the CM IV procedure (Supplemental Table 2). In multivariable analysis, the probability of postoperative SR was significantly reduced in patients with increased LA diameter (OR: 0.48, $p = 0.045$). As risk factors for mortality after surgical ablation, univariate analysis identified older age at surgery, long-standing persistent AF, increased LA diameter, dialysis, and prolonged stay i

Table 3: Permanent pacemaker implantation after the CM IV procedure.

	Variables		
Rhythm before CM IV	Paroxysmal AF ($n = 36$)	Persistent AF ($n = 40$)	Long-standing persistent AF ($n = 16$)
Pacemaker total	5 (13.9)	8 (20)	5 (31.3)
Indication			
AV block III°	2	4	2
TBS	1	4	3
Sick sinus syndrome	1	0	0
Other	1	0	0
Pacemaker mode			
DDD	3	6	4
VVI	1	1	1
CRT	1	1	0
Timing			
In-hospital	2	7	3
3-month FU	0	0	1
6-month FU	0	0	0
≥12-month FU	3	1	1

Values are expressed as n (%). AF: atrial fibrillation, AV: atrioventricular, CM: Cox-maze, CRT: cardiac resynchronization therapy, DDD: dual-chamber pacing and sensing, FU: follow-up, TBS: tachycardia-bradycardia syndrome, VVI: ventricle pacing and sensing.

n the intensive care unit (ICU) (Supplemental Table 3). In the multivariable Cox regression analysis, long-standing persistent AF (HR: 5.35, $p = 0.02$), need for postoperative dialysis (HR: 12.91, $p = 0.02$), and prolonged ICU stay (HR: 2.21, $p = 0.01$) were identified as independent risk factors for mortality.

4. Discussion

The CM IV procedure using cryothermal energy for the creation of transmural and continuous ablation lines represents the current iteration of the CM procedure. According to the current guidelines, surgical ablation is recommended as a stand-alone therapy for patients refractory to class I/III antiarrhythmic drugs or catheter-based therapy (American guidelines: Class IIa, Level B) [4], or as a concomitant therapy when associated with structural valve disease and coronary artery disease (European guidelines: Class IIa, Level A) [4] (American guidelines: Class I, Level B) [7].

4.1. Success Rate of Surgical Ablation and Continuity of Sinus Rhythm. In patients with stand-alone AF, the CM IV procedure using bipolar radiofrequency and cryoenergy is associated with 1-year freedom from AF rates of 90% and 76% [10, 16, 17]. However, as AF is often coincident with other cardiac diseases, the CM IV procedure is frequently performed as a concomitant surgical procedure [18]. In the meta-analysis by Sef et al., a 92% rate of freedom from AF by the Cox-maze procedure and pulmonary vein isolation was described and the concomitant Cox-maze procedure was associated with better midterm freedom from AF when compared to pulmonary vein isolation [19]. However, no pulmonary vein isolation was performed in the present investigation. In the prospective, multicenter, randomized controlled trial by Gilinov et al., patients with long-standing persistent AF and MV disease requiring surgical intervention were divided into two groups: either undergoing surgical ablation or no ablation [11]. At 12 months after surgery, more patients in whom surgical ablation had been performed were free from AF (63.2% vs. 29.4%, $p < 0.001$). In the present investigation, the rate of SR at 1 year after the concomitant biatrial CM IV procedure was 59.6% and 1-year survival was 89%. These numbers are in line with the study by Gilinov et al. as persistent AF and long-standing persistent AF were prevailing in the majority of our patient cohort with enlarged atrial diameters and valvular heart disease. Abreu Filho et al. reported a postoperative rate of SR of 63% at 3 months and of 79% at 12 months in patients with rheumatic MV disease and long-standing persistent AF who underwent MV surgery and surgical ablation using cryothermal energy [20]. The increased rate of SR at 12 months after surgical ablation in the publication by Abreu Filho et al. is due to their 15 years lower patients' mean age with less atrial remodeling and fibrosis when compared to the present investigation. In the multicenter prospective registry by Gerdisch et al., excellent 1-year freedom from AF rates by concomitant CM IV was reported ranging from 82% to 95% [21]. In the most recent meta-analysis by Gao et al., restoration of SR after concomitant CM IV procedure has been 66.5% at discharge, 75.5% at 6 months, and 67.1% at 12 months (67.1% vs. 21.4%) of follow-up, which is slightly higher than in our patient cohort of mixed concomitant surgical procedures [22]. However, reports on the procedural efficacy of the concomitant CM IV procedure are still heterogeneous due to the lack of a precise description and nomenclature. In the present investigation, we could show that SR continued in 49% (24/49) at 3 and 6 months after surgical ablation and persisted in 29% (14/49) 1 year after CM IV. In 4% (2/49), conversion of SR to AF or OA at 12-month follow-up was seen. Despite SR at hospital discharge, AF or OA was detected in 35% of patients (17/49) at 3- or 6-month follow-up and conversion to SR at 12-month follow-up was seen in 10% (5/49). In 14% of patients (7/49), AF or OA prevailed at

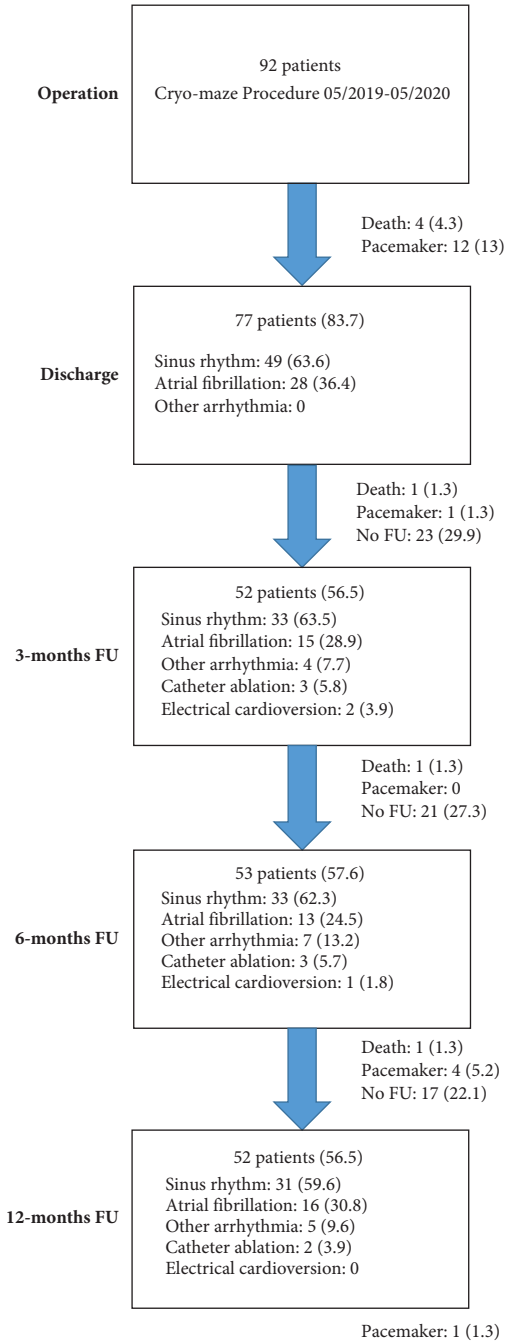


Figure 2: Flowchart of survival, heart rhythm, pacemaker implantation, and interventions. FU: follow-up.

1 year after CM IV. In patients with AF or OA, at hospital discharge, we could show that AF or OA continued in 39% (11/28) during the 12-month follow-up, and in 29% of patients (8/28), a stable SR was detected. We could also show that SR was significantly more times achieved in patients with preoperative paroxysmal than long-standing persistent AF. However, data on success rate after CM IV procedure stratified by mode of AF are rare.

4.2. Predictors for Postoperative Sinus Rhythm and Risk Factors for Mortality. We could also demonstrate that patients with long-standing persistent AF and increased left atrial diameter were significantly less likely to achieve SR. The increase in the LA size is an established risk factor for the recurrence of atrial tachyarrhythmias [23, 24]. In the review by Sunderland et al., no clear cut-off value for LA size was identified; however, larger LA size was a predictor of maze surgery failure in nine out of 12 papers [25]. In the investigation by Khiabani et al., left atrial size and nonparoxysmal AF were identified as relevant predictors of late recurrence of AF [26]. As atrial structural remodeling and fibrosis increase in older patients, age ≥75 years was linked with a significantly reduced success rate of the CM IV procedure [27]. In the present investigation, age at the time of surgery did not significantly influence the rate of SR after CM IV. This different effect of age on the efficacy of the CM IV procedure might be explained by the lower age at the time of surgery and less frequent comorbidities in our study. In the present investigation, late mortality was 5.4%, which is comparable to the reported mortality by Gilinov et al. [11]. Long-standing persistent AF, need for postoperative dialysis, and prolonged stay in the ICU were identified as independent risk factors for mortality after the CM IV procedure. Prolonged cardiopulmonary bypass time required to perform CM IV lesions predisposes to acute kidney injury with the need for postoperative dialysis, especially in patients with preoperative renal disease [28].

4.3. Permanent Pacemaker Implantation. Permanent pacemaker implantation is a well-known complication after the CM IV procedure with implantation rates ranging from 15% to 20% [29–31]. In our study, PPM implantation was necessary in 19.6% of patients with 13% of patients requiring early in-hospital PPM implantation. These values are in line with the PPM rates reported by Gilinov et al. who describe an early PPM implantation rate of 17% [11]. Our relatively high rate of PPM implantations may be attributable to the facts that our entire cohort underwent concomitant valve surgery or coronary artery bypass grafting plus valve surgery, enhanced extracardiac dissection due to prior cardiac surgery, and previous catheter ablation in 17% of patients. Another contributing factor is the rate of double (55%) and triple (5.4%) valve surgery increasing the risk of atrioventricular block. Ad et al. showed that patients with multiple valve procedures were at the greatest risk for in-hospital PPM implantation [32]. The biatrial lesion set was identified as a significant predictor for PPM implantation after surgical AF ablation [33]. However, in the present investigation, PPM interrogation at the last follow-up revealed that stimulation was only required in 9% of patients independent of the preoperative mode of AF. In contrast to our in-hospital timing of rather swift PPM implantation, a more liberal wait-and-see approach for the indication of PPM implantation may be advocated.

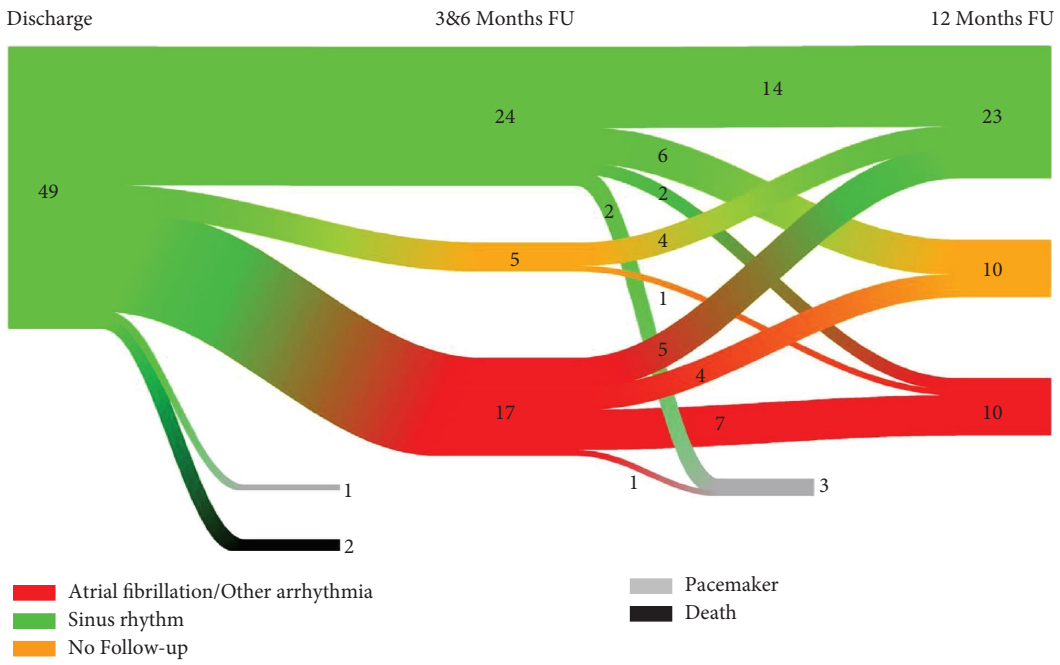


Figure 3: Riverplot of patients with sinus rhythm during the follow-up of 12 months. Red: atrial fibrillation/other arrhythmia; green: sinus rhythm; orange: no follow-up; grey: pacemaker; and black: death. FU: follow-up.

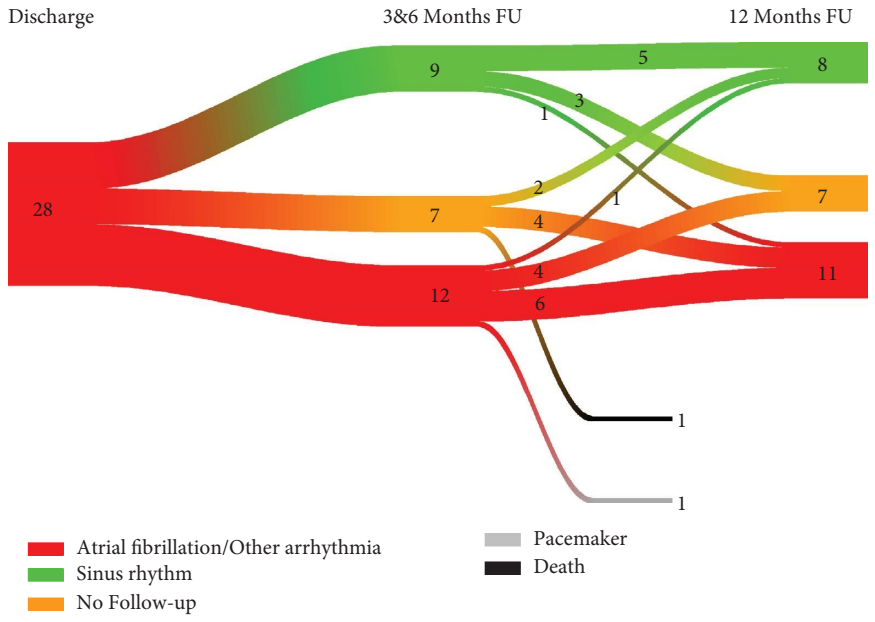


Figure 4: Riverplot of patients with atrial fibrillation during the follow-up of 12 months. Red: atrial fibrillation/other arrhythmia; green: sinus rhythm; orange: no follow-up; grey: pacemaker; and black: death. FU: follow-up.

4.4. Limitations. The present single-center study was limited by its retrospective design and the small number of patients with available 1-year follow-up. Other limiting factors were the inconsistencies of the availability of 24-hour electrocardiogram monitoring and continuous detection of atrial conduction disturbances. Complete 12-month follow-up was obtained only in a fraction of patients with single ECG being snapshots in time, which might underreport the recurrence of AF or OA. Thus, continuous monitoring via 24-hour Holter ECG or wearable cardiac monitors is crucial in improving the outcomes of patients after the surgical biatrial CM IV procedure. Alterations from the standard postoperative regime related to amiodarone might have impacted the conversion rate to SR. The rate of double and triple valve surgery might have contributed to the increased rate of PPM implantation after CM IV. Further limitations of the present investigation include the heterogeneity of the patient cohort, the concomitant procedures, and the 14%

rate of previous cardiac surgery, which might have diluted the efficacy of the CM IV procedure. The difference in surgeon's experience performing the concomitant CM IV procedure may have affected our outcome parameters in a way not covered by our analysis. Due to the limited follow-up adherence in the present investigation, another prospective study has been initiated at our department with a longer follow-up period, permanent ECG monitoring via wearable smartwatches, and with a suitable comparative group.

5. Conclusions

The concomitant CM IV procedure is a viable treatment option for patients with AF. The risk of PPM implantation following the CM IV procedure should be considered during the decision-making process although PPM implantation was not associated with significantly increased mortality risk. Patients with long-standing persistent AF and increased LA diameter should be monitored closely after ablation surgery as they were significantly less likely to achieve permanent SR.

Data Availability

The data underlying this article will be shared on reasonable request to the corresponding author.

Conflicts of Interest

Dr. Krane is a physician proctor and a member of the medical advisory board for JOMDD, a physician proctor for Peter Duschek, and a medical consultant for EVOTEC and Moderna, and has received speakers' honoraria from Medtronic and Terumo. The other authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Authors' Contributions

Markus Krane and Keti Vitanova contributed equally.

Acknowledgments

Open Access funding was enabled and organized by Projekt DEAL.

Supplementary Materials

Supplemental Table 1: Biatrial Cox-maze IV and concomitant procedures. Supplemental Table 2: Logistic regression for sinus rhythm after maze procedure. Supplemental Table 3: Risk factor analysis for mortality after the maze procedure. Supplemental Figure 1: Overall survival after the CM IV procedure. Supplemental Figure 2: Survival after the CM IV procedure in patients with long-standing persistent atrial fibrillation (green) and in patients without (blue). Supplemental Figure 3: Heart rhythm at the last follow-up for patients with preoperative paroxysmal (blue), persistent (orange), and long-standing persistent atrial fibrillation (grey). STROBE-checklist. (*Supplementary Materials*)

References

[1] S. A. Roberts, C. Diaz, P. E. Nolan et al., "Effectiveness and costs of digoxin treatment for atrial fibrillation and flutter," *The American Journal of Cardiology*, vol. 72, no. 7, pp. 567–573, 1993.

[2] J. Xu, J. G. Y. Luc, and K. Phan, "Atrial fibrillation: review of current treatment strategies," *Journal of Thoracic Disease*, vol. 8, no. 9, pp. E886–E900, 2016.

[3] C. A. J. Van der Heijden, E. Bidar, and B. Maesen, "Concomitant arrhythmia surgery should be a standard procedure in AF patients undergoing cardiac surgery," *Journal of Cardiac Surgery*, vol. 37, no. 10, pp. 3014-3015, 2022.

[4] G. Hindricks, T. Potpara, N. Dagres et al., "2020 ESC Guidelines for the diagnosis and management of atrial fibrillation developed in collaboration with the European Association for Cardio-Thoracic Surgery (EACTS)," *European Heart Journal*, vol. 42, no. 5, pp. 373–498, 2021.

[5] E. Lee, E.-K. Choi, K.-D. Han et al., "Mortality and causes of death in patients with atrial fibrillation: a nationwide population-based study," *PLoS One*, vol. 13, no. 12, Article ID e0209687, 2018.

[6] M. G. Whitbeck, R. J. Charnigo, J. Shah et al., "QRS duration predicts death and hospitalization among patients with atrial fibrillation irrespective of heart failure: evidence from the AFFIRM study," *Europace*, vol. 16, no. 6, pp. 803–811, 2014.

[7] V. Badhwar, J. S. Rankin, R. J. Damiano Jr et al., "The society of thoracic surgeons 2017 clinical practice guidelines for the surgical treatment of atrial fibrillation," *The Annals of Thoracic Surgery*, vol. 103, no. 1, pp. 329–341, 2017.

[8] J. L. Cox, R. B. Schuessler, and J. P. Boineau, "The development of the Maze procedure for the treatment of atrial fibrillation," *Seminars in Thoracic and Cardiovascular Surgery*, vol. 12, no. 1, pp. 2–14, 2000.

[9] C. Ruaengsri, M. R. Schill, A. J. Khiabani, R. B. Schuessler, S. J. Melby, and R. J. Damiano Jr, "The Cox-maze IV procedure in its second decade: still the gold standard?" *European Journal of Cardio-Thoracic Surgery*, vol. 53, no. suppl_1, pp. i19–i25, 2018.

[10] T. Weimar, M. S. Bailey, Y. Watanabe et al., "The Cox-maze IV procedure for lone atrial fibrillation: a single center experience in 100 consecutive patients," *Journal of Interventional Cardiac Electrophysiology*, vol. 31, no. 1, pp. 47–54, 2011.

[11] A. M. Gillinov, A. C. Gelijns, M. K. Parides et al., "Surgical ablation of atrial fibrillation during mitral-valve surgery," *New England Journal of Medicine*, vol. 372, no. 15, pp. 1399–1409, 2015.

[12] T. Kakuta, S. Fukushima, K. Minami et al., "Incidence of and risk factors for pacemaker implantation after the modified Cryo-Maze procedure for atrial fibrillation," *The Journal of Thoracic and Cardiovascular Surgery*, vol. 166, no. 3, pp. 755–766.e1, 2023.

[13] R. J. Damiano, F. H. Schwartz, M. S. Bailey et al., "The Cox Maze IV procedure: predictors of late recurrence," *The Journal of Thoracic and Cardiovascular Surgery*, vol. 141, no. 1, pp. 113–121, 2011.

[14] C. T. January, L. S. Wann, J. S. Alpert et al., "2014 AHA/ACC/HRS guideline for the management of patients with atrial fibrillation: a report of the American college of Cardiology/American heart association task force on practice guidelines and the heart rhythm society," *Circulation*, vol. 130, no. 23, pp. e199–e267, 2014.

[15] R. M. Lang, M. Bierig, R. B. Devereux et al., "Recommendations for chamber quantification: a report from the American society of echocardiography's guidelines and standards committee and the chamber quantification writing group, developed in conjunction with the European association of echocardiography, a branch of the European society of Cardiology," *Journal of the American Society of Echocardiography*, vol. 18, no. 12, pp. 1440–1463, 2005.

[16] T. Weimar, S. Schena, M. S. Bailey et al., "The cox-maze procedure for lone atrial fibrillation: a single-center experience over 2 decades," *Circulation: Arrhythmia and Electrophysiology*, vol. 5, no. 1, pp. 8–14, 2012.

[17] B. Chiappini, R. Di Bartolomeo, and G. Marinelli, "Radiofrequency ablation for atrial fibrillation: different approaches," *Asian Cardiovascular & Thoracic Annals*, vol. 12, no. 3, pp. 272–277, 2004.

[18] J. S. Gammie, M. Haddad, S. Milford-Beland et al., "Atrial fibrillation correction surgery: lessons from the society of thoracic surgeons national cardiac database," *The Annals of Thoracic Surgery*, vol. 85, no. 3, pp. 909–914, 2008.

[19] D. Sef, V. Trkulja, S. G. Raja, J. Hooper, and M. I. Turina, "Comparing mid-term outcomes of Cox-Maze procedure and pulmonary vein isolation for atrial fibrillation after concomitant mitral valve surgery: a systematic review," *Journal of Cardiac Surgery*, vol. 37, no. 11, pp. 3801–3810, 2022.

[20] C. A. Abreu Filho, L. A. Lisboa, L. A. Dallan et al., "Effectiveness of the maze procedure using cooled-tip radiofrequency ablation in patients with permanent atrial fibrillation and rheumatic mitral valve disease," *Circulation*, vol. 112, no. 9 Suppl, pp. I20–I25, 2005.

[21] M. Gerdisch, E. Lehr, G. Dunnington et al., "Mid-term outcomes of concomitant Cox-Maze IV: results from a multicenter prospective registry," *Journal of Cardiac Surgery*, vol. 37, no. 10, pp. 3006–3013, 2022.

[22] Y. Gao, H. Luo, R. Yang et al., "Safety and efficacy of Cox-Maze procedure for atrial fibrillation during mitral valve surgery: a meta-analysis of randomized controlled trials," *Journal of Cardiothoracic Surgery*, vol. 19, no. 1, p. 140, 2024.

[23] J. Kamata, K. Kawazoe, H. Izumoto et al., "Predictors of sinus rhythm restoration after Cox maze procedure concomitant with other cardiac operations," *The Annals of Thoracic Surgery*, vol. 64, no. 2, pp. 394–398, 1997.

[24] J. Kobayashi, Y. Kosakai, K. Nakano, Y. Sasako, K. Eishi, and F. Yamamoto, "Improved success rate of the maze procedure in mitral valve disease by new criteria for patients' selection," *European Journal of Cardio-Thoracic Surgery*, vol. 13, no. 3, pp. 247–252, 1998.

[25] N. Sunderland, M. Maruthappu, and M. Nagendran, "What size of left atrium significantly impairs the success of maze surgery for atrial fibrillation?" *Interactive Cardiovascular and Thoracic Surgery*, vol. 13, no. 3, pp. 332–338, 2011.

[26] A. J. Khiabani, R. M. MacGregor, N. H. Bakir et al., "The long-term outcomes and durability of the Cox-Maze IV procedure for atrial fibrillation," *The Journal of Thoracic and Cardiovascular Surgery*, vol. 163, no. 2, pp. 629–641, 2022.

[27] R. M. MacGregor, A. J. Khiabani, N. H. Bakir et al., "Impact of age on atrial fibrillation recurrence following surgical ablation," *The Journal of Thoracic and Cardiovascular Surgery*, vol. 162, no. 5, pp. 1516–1528, 2021.

[28] H. J. Hong, Y. Lee, S. H. Kim et al., "Incidence and risk factors of acute kidney injury after maze operation in patients with rheumatic mitral valve disease," *Journal of Thoracic Disease*, vol. 14, no. 9, pp. 3408–3414, 2022.

[29] S. M. Prasad, H. S. Maniar, C. J. Camillo et al., "The Cox Maze III procedure for atrial fibrillation: long-term efficacy in patients undergoing lone versus concomitant procedures," *The Journal of Thoracic and Cardiovascular Surgery*, vol. 126, no. 6, pp. 1822–1827, 2003.

[30] H. V. Schaff, J. A. Dearani, R. G. Daly, T. A. Orszulak, and G. K. Danielson, "Cox-maze procedure for atrial fibrillation: mayo Clinic experience," *Seminars in Thoracic and Cardiovascular Surgery*, vol. 12, no. 1, pp. 30–37, 2000.

[31] J. L. Cox, N. Ad, A. Churyla et al., "The maze procedure and postoperative pacemakers," *The Annals of Thoracic Surgery*, vol. 106, no. 5, pp. 1561–1569, 2018.

[32] N. Ad, S. D. Holmes, R. Ali, G. Pritchard, and D. Lamont, "A single center's experience with pacemaker implantation after the Cox maze procedure for atrial fibrillation," *The Journal of Thoracic and Cardiovascular Surgery*, vol. 154, no. 1, pp. 139–146, 2017.

[33] S. Pecha, T. Schäfer, Y. Yildirim et al., "Predictors for permanent pacemaker implantation after concomitant surgical ablation for atrial fibrillation," *The Journal of Thoracic and Cardiovascular Surgery*, vol. 147, no. 3, pp. 984–988, 2014.