Interdisciplinary CardioVascular and Thoracic Surgery 2023, 36(3), ivad030
https://doi.org/10.1093/icvts/ivad030 Advance Access publication 14 February 2023

Cite this article as: Gollmann-Tepeköylü C, Nägele F, Höfer D, Holfeld J, Hirsch J, Oezpeker CU *et al.* A qualitative improvement program for minimally invasive mitral surgery: technical advancements ameliorate outcome and operative times. Interdiscip CardioVasc Thorac Surg 2023; doi:10.1093/icvts/ivad030.

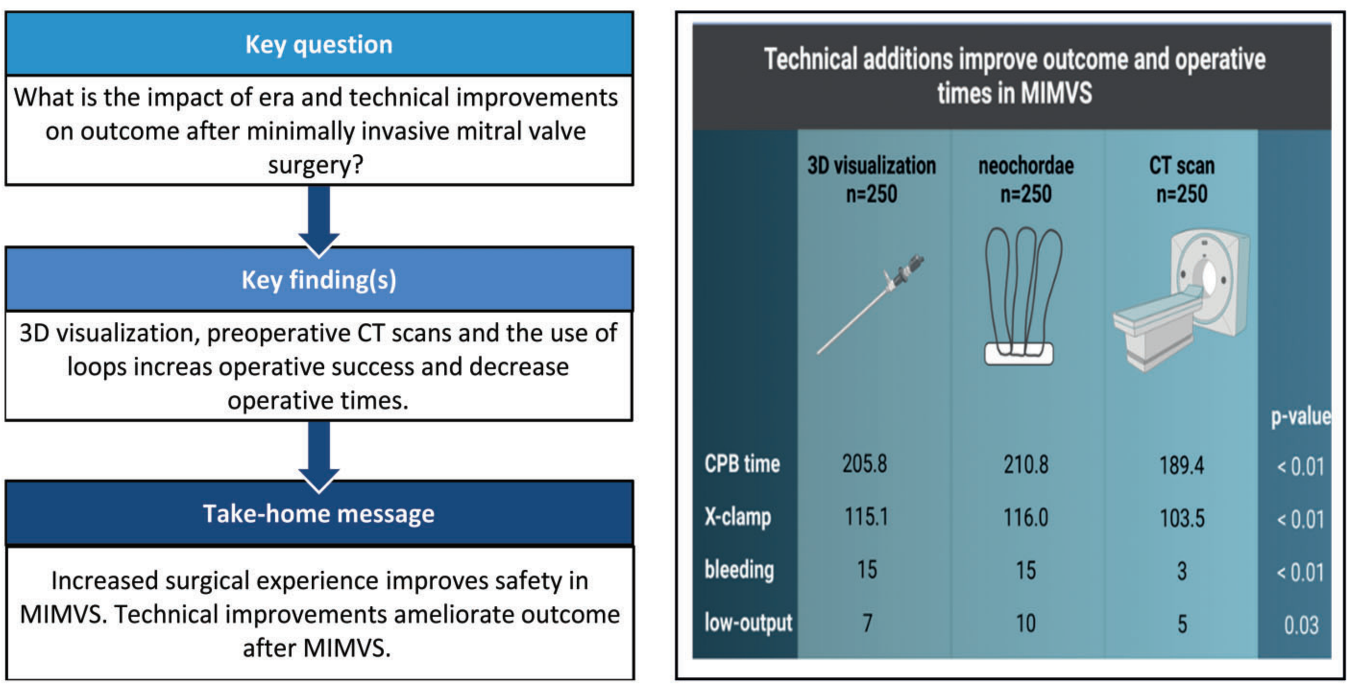
A qualitative improvement program for minimally invasive mitral surgery: technical advancements ameliorate outcome and operative times

Can Gollmann-Tepeköylü†, Felix Nägele†, Daniel Höfer, Johannes Holfeld, Jakob Hirsch, Cenk Ulvi Oezpeker, Elfriede Ruttmann-Ulmer, Juliane Kilo, Herbert Hangler, Ludwig Müller, Michael Grimm and Nikolaos Bonaros *

Department of Cardiac Surgery, Medical University of Innsbruck, Innsbruck, Austria

* Corresponding author. Department of Cardiac Surgery, Medical University of Innsbruck, Anichstr. 35, 6020 Innsbruck, Austria. Tel: +43-512-504-22501; e-mail: nikolaos.bonaros@i-med.ac.at (N. Bonaros).

Received 31 March 2022; received in revised form 12 October 2022; accepted 5 February 2023



Abstract

OBJECTIVES: Minimally invasive mitral valve surgery (MIMVS) has evolved over the last 2 decades. The aim of the study was to identify the impact of era and technical improvements on perioperative outcome after MIMVS.

†The first two authors contributed equally to this work.
Presented at the EACTS 35th Annual Meeting, October 13th-16th 2021, Barcelona, Spain.

METHODS: A tota of 1000 patients (mean age: 60.8 ± 12.7 years, 60.3% male) underwent video-assisted or totally endoscopic MIMVS between 2001 and 2020 in a single institution. Three technical modalities were introduced during the observed period: (i) 3D visualization, (ii) use of premeasured artificial chordae (PTFE loops) and (iii) preoperative CT scans. Comparisons were made before and after the introduction of technical improvements.

RESULTS: A total of 741 patients underwent isolated mitral valve (MV) procedure, whereas 259 received concomitant procedures. These consisted of tricuspid valve repair (208), left atrium ablation (145) and persistent foramen ovale or atrial septum defect (ASD) closure (172). The aetiology was degenerative in 738 (73.8%) patients and functional in 101 patients (10.1%). A total of 900 patients received MV repair (90%), and 100 patients (10%) underwent MV replacement. Perioperative survival was 99.1%, and periprocedural success 93.5% with a periprocedural safety of 96.3%. Improvement in periprocedural safety attributed to the lower rates of postoperative low output ($P = 0.025$) and less reoperations for bleeding ($P < 0.001$). 3D visualization improved cross-clamp ($P = 0.001$) but not cardiopulmonary bypass times. The use of loops and preoperative CT scan both had no impact on periprocedural success or safety but improved cardiopulmonary bypass and cross-clamp times (both $P < 0.001$).

CONCLUSIONS: Increased surgical experience improves safety in MIMVS. Technical improvements are related to increased operative success and decreased operative times in patients undergoing MIMVS.

Keywords: Minimally invasive mitral valve surgery • Technical innovation • Mitral valve disease

ABBREVIATIONS

AML	Anterior mitral leaflet
CPB	Cardiopulmonary bypass
MIMVS	Minimally invasive mitral valve surgery
MR	Mitral regurgitation
MV	Mitral valve
PML	Posterior mitral leaflet
X-clamp	Cross-clamp

INTRODUCTION

Mitral valve (MV) surgery remains the treatment of choice for operable symptomatic patients with MV disease [1, 2]. The surgeon's ultimate goal remains a perfect and durable repair if possible. Over the last 2 decades minimally invasive mitral valve surgery (MIMVS) has been established as feasible method for this purpose in specialized centres with low rates of conversion to sternotomy, 30-day mortality or stroke [3–5]. Successful repair with durable results can be achieved in patients with anterior, posterior or bileaflet prolapse with 5-year survival rates of 87% and 5-year freedom from cardiac reoperation rates of 96% [6]. MIMVS is even feasible for the repair of MV in Barlow's disease [7].

Long-term follow-up data reveal 20-year reoperation-free survival of 60%, whereas the incidence of cardiac and valve-related deaths was 12% and reoperation rate on the MV 5%. Seventeen percentage of the patients had a bleeding or thromboembolic event [8, 9]. However, the probability to suffer from recurrent mitral regurgitation (MR) was as high as 13%, risk factors for the development of recurrent MR included age, heart block, MV repair without annuloplasty and the degree of myxomatous degeneration [8, 10].

Various technical approaches have been described for durable MV repair including implantation of artificial chordae, posterior mitral leaflet (PML) or anterior mitral leaflet (AML) resection, Alfieri stitch, commissural plication, chordal transfer resection [11, 12]. Performing concomitant procedures including tricuspid valve (TV) repair, atrial septal defect closure or cryoablation is also safe via a minimally invasive approach after MV repair or replacement [11, 13]. While a 'respect rather than resect' approach has been postulated and preferred by many MV surgeons, recent data of a randomized, controlled trial could not confirm superiority of leaflet preservation over leaflet resection in terms of transmitral gradients or rates of regurgitation 12 months after surgery at peak exercise [14].

Despite the ever-growing number of percutaneous MV devices flooding the medical market under industrial pressure, MV repair has remained the treatment of choice with good results making moderately severe or severe MR after MV repair unlikely in the decade after surgery [15, 16]. To further compete with percutaneous devices and provide optimal results for patients with MV disease, there is an urgent need to even further improve clinical results of MIMVS due to increased experience and ongoing technical developments. Key factors of new developments include remote access perfusion [17], improved cardioplegic solutions [18], the routine use of 3D-endoscopy for valve repair [19], the use of chordal replacement techniques [20] and the implementation of systematic preoperative CT scans [21]. The aim of this study was to identify the impact of era and technical improvements on perioperative outcome after MIMVS. The introduced improvements were not part of a standardized quality improvement program. Nevertheless, they are considered as part of a Plan–Do–Study–Act cycle for a single institution.

METHODS

Ethics statement

The study was approved by the institutional ethical committee of the Medical University of Innsbruck (approval 1203/2019) on 13 February 2020.

Study design

Data were derived from a consecutive series of patients undergoing MV surgery via anterolateral thoracotomy and 2D or 3D endoscopy between March 2001 and May 2020 at the University Hospital Innsbruck, Austria. Data were acquired between December 2019 and November 2020 by telephone interviews with the patients directly, or indirectly though the family physicians or the referring peripheral hospitals (completeness 89.3% of the survivors). The time interval between operation and follow-up was used for calculations of time-dependent variables. Patients without an event were censored at the end of the follow-up. Survival data were acquired by the national death registry of Austria (completeness 98.9%). A total of 1000 patients (mean age: 60.8 ± 12.7 years, 60.3% male) underwent endoscopic MV surgery. Three technical innovations were introduced during the observed period of 19 years: (i) fully endoscopic technique through 3D visualization, (ii) the adoption of premeasured polytetrafluoroethylen (PTFE) chordae loops for prolapse correction and (iii) the implementation of a preoperative CT scan to exclude unsuitable candidates for MIMVS.

Operative technique

Patients were operated in 30° right supine position as described previously [22]. From 2017 onwards, all patients underwent preoperative computer tomography (CT) scan to exclude severe atherosclerosis or kinking of the femoro-iliac vessels and the aorta as well as major mitral annular calcifications. Cardiopulmonary bypass was installed via femoro-femoral cannulation. Femoral cannulation is performed in our centre routinely via a surgical approach. An additional distal leg perfusion was used in a standardized fashion since 2013 to avoid ischaemic complications of the leg. An additional venous cannula was inserted in the right jugular vein in case of right heart surgery or patients with increased body surface area to allow total cardiopulmonary bypass and optimal drainage. A periareolar or a 4- to 5-cm-long skincut lateral to the nipple or a similar incision in the submammary fold in female patients was made to allow access to the 4th intercostal space. The 3rd intercostal space on the anterior axillary line was used for the endoscope and the transthoracic clamp. A 30° 2D scope was used until 2014 and a 3D scope (Einstein-Vision, Aesculap, Tuttlingen, Germany) was introduced thereafter. Since 2015 a typical procedure has been performed by 3D endoscopy and a soft tissue retractor (Alexis Wound-protector, Applied Medical, Santa Margarita, CA) without the use of a rib retractor. After pericardial incision, the cardioplegia line was inserted in the ascending aorta and externalized in the 3rd intercostal space. The same incision was used for the atrial retractor (Geister, Tuttlingen, Germany). Common mitral repair techniques including chordal replacement (single PTFE chords, secondary chord transfer or pre-fabricated PTFE loops), leaflet resection, sliding plasty or indentation closure were applied. A semi-rigid complete annuloplasty ring was used in all procedures. When indicated, concomitant left atrial or bi-atrial ablation was performed for atrial fibrillation in addition to closure of the left atrial appendage. Older patients with long persistent atrial fibrillation and enlarged left atria were not deemed to be good candidates for rhythm correction therapy. All patients with an indication for left atrial appendage (LAA) closure receive external atrial clipping in our current practice. The LAA was closed by a double layer of endocardial suture or atrial clipping, according to the surgeons' preference. Moreover, a tricuspid valve repair was performed in all patients with severe tricuspid valve regurgitation or annular dilatation above 21 mm/m^2 BSA. The types of procedures performed are shown in Table 2. Six main surgeons performed the procedures which in the frame of a university hospital also included many teaching cases. The main reasons for non-eligibility for MIMVS were either concomitant coronary/other valve disease or calcifications of the iliac artery/abdominal aorta precluding retrograde perfusion as described previously [22]. The allocation of the patient to conventional or MIMVS was dictated by institutional protocols. During the program development (2001–2006), patients with complex mitral pathology, concomitant tricuspid disease, need for left atrial ablation, pulmonary hypertension > moderate, impaired left ventricular or renal function and older age (>80) were not deemed as candidates for MIMVS. This decision was made to keep the risk of the procedure predictable and to minimize the risk of technical failures due to the limited experience.

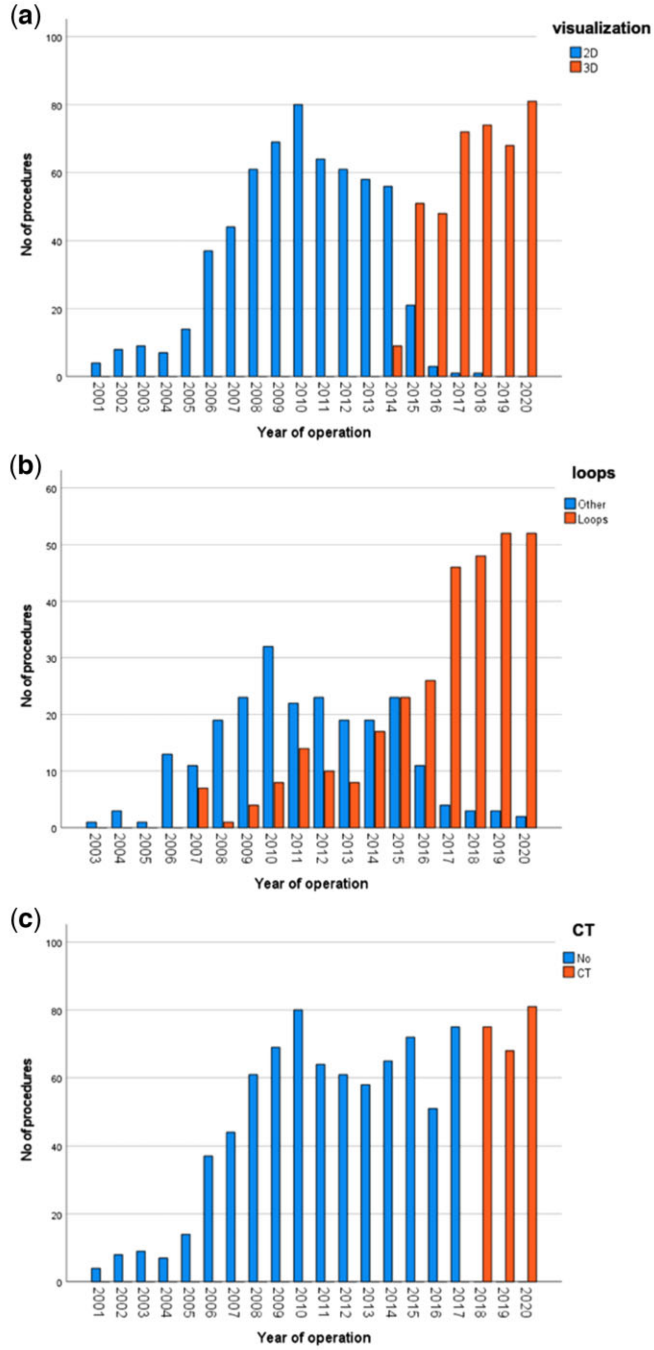


Figure 1: Implementation of technical improvements. Number of procedures with implemented technical improvements.

Definitions

Operative success was defined as a successful primary mitral repair without conversion to valve replacement or to larger thoracic incisions, no residual MR > mild and no need for reoperation for any reason within the first 30 days. The prerequisite of conversion was attempted repair of the valve. In patients with a priori indication for valve replacement, this was not considered as conversion from repair to replacement. Perioperative safety was defined as freedom from death, perioperative myocardial infarction (4th Universal Definition of Myocardial infarction), stroke, extracorporeal membrane oxygenation (ECMO) support or reoperation for bleeding in the perioperative period (30 days). Reoperation-free survival was used as a long-term efficacy end point defined as a composite of freedom from death and reoperation at follow-up.

Retrospective capture of valve-related complications in follow-up included native (residual MR) or prosthetic valve dysfunction (paravalvular leakage, valve degeneration, valve thrombosis) and MV endocarditis [4].

Introduced changes

3D endoscopy has been used since 2014 (Fig. 1a). Loop technique was introduced in 2008 and was used as a default technique to repair leaflet prolapse since 2015 (Fig. 1b). CT scan has been performed only sporadically before 2017; however, after 2018, all patients underwent a preoperative CT scan (Fig. 1c).

Statistical analysis

Data are presented as mean ± standard deviation for continuous variables and absolute numbers as well as percentages for categorical variables. Comparisons were made before and after the introduction of technical improvements by Chi-square test and one-way analysis of variance (ANOVA). Continuous variables were compared by Student's *t*-test or the Mann–Whitney *U*-test. A two-sided *P*-value of <0.05 was considered as statistically significant. Data documentation and statistical analysis were performed using SPSS 24.0 (IBM Corp.).

RESULTS

We allocated a total of 1000 patients undergoing endoscopic MV surgery (mean age: 60.8 ± 12.7 years, 60.5% male) to 3 groups according to the introduced innovation. A detailed patient description of the patients is displayed in Table 1. 4.7% of the patients hat concomitant mitral stenosis, whereas 97.4% suffered from severe MR. The majority of the patient suffered from Carpentier type II MR (76.4%), 11.4% from type I, 9.9% from type IIIa and 2.3% from type IIIb (Table 2). MV disease was of degenerative origin in 75.6%, functional in 13.6% and rheumatic in 9.7%. 1.1% were suffering from endocarditis. AML prolapse was

Table 1: Patient characteristics

	All MVR patients *N* = 1000	3D *N* = 484	Loops *N* = 347	CT *N* = 221
Demographic characteristics				
Female, *n* (%)	395 (39.50)	177 (36.57)	117 (33.72)	79 (35.75)
Age, mean (SD)	60.79 (12.70)	60.35 (12.38)	59.27 (12.81)	59.71 (12.68)
BSA, mean (SD)	1.89 (0.22)	1.90 (0.23)	1.90 (0.23)	1.90 (0.23)
BMI, mean (SD)	25.03 (4.03)	24.93 (3.97)	24.82 (4.03)	24.83 (4.21)
Pre-existing conditions				
EuroScoreII, mean (SD)	1.96 (1.78)	1.80 (1.65)	1.75 (1.70)	1.87 (1.97)
eGFR, mean (SD)	82.18 (26.96)	83.36 (28.09)	85.24 (28.15)	85.57 (28.46)
LVEF, mean (SD)	57.89 (9.65)	59.29 (9.42)	58.98 (9.39)	58.19 (9.93)
Hypertension, *n* (%)	463 (46.30)	229 (47.31)	169 (48.70)	106 (47.96)
Diabetes, *n* (%)	39 (3.90)	16 (3.31)	12 (3.46)	7 (3.17)
Dyslipidaemia, *n* (%)	276 (27.60)	139 (28.72)	105 (30.26)	74 (33.48)
Smoking, *n* (%)	79 (7.90)	44 (9.09)	34 (9.80)	15 (6.79)
COPD, *n* (%)	32 (3.20)	17 (3.51)	12 (3.46)	5 (2.26)
Dialysis, *n* (%)	4 (0.40)	2 (0.41)	1 (0.29)	0 (0.00)
PAD, *n* (%)	2 (0.20)	1 (0.21)	1 (0.29)	0 (0.00)
CVD, *n* (%)	7 (0.70)	5 (1.03)	3 (0.86)	2 (0.90)
CAD, *n* (%)	27 (2.70)	15 (3.10)	7 (2.02)	3 (1.36)
Previous PCI, *n* (%)	20 (2.00)	11 (2.27)	3 (0.86)	3 (1.36)
NYHA, *n* (%)				
1	162 (16.20)	118 (24.38)	71 (20.46)	37 (16.74)
2	401 (40.10)	205 (42.36)	160 (46.11)	106 (47.96)
3	422 (42.20)	156 (32.23)	113 (32.56)	76 (34.39)
4	15 (1.50)	5 (1.03)	3 (0.86)	2 (0.90)
aFib, *n* (%)	354 (35.40)	159 (32.85)	112 (32.28)	73 (33.03)
Prev. cardiac surgery, *n* (%)	42 (4.20)	25 (5.17)	21 (6.05)	14 (6.33)
Prev. MV surgery, *n* (%)	14 (1.40)	9 (1.86)	7 (2.02)	4 (1.81)
pHT, *n* (%)				
No	751 (75.10)	384 (79.34)	292 (84.15)	189 (85.52)
sPAP 51–55 mmHg	202 (20.20)	83 (17.15)	47 (13.54)	28 (12.67)
sPAP >55 mmHg	47 (4.70)	17 (3.51)	8 (2.31)	4 (1.81)

MV: mitral valve; SD: standard deviation; aFib: atrial fibrillation; BMI: body mass index; BSA: body surface area; CAD: coronary artery disease; COPD: chronic obstructive pulmonary artery disease; PAD: peripheral arterial disease; PAD: peripheral arterial disease; eGFR: estimated glomerular filtration rate; EuroScore:EuroSCORE; LVEF: left ventricular ejection fraction; MVR: mitral valve repair; NYHA: New York heart association; PCI: percutaneous coronary intervention; PHT: pulmonary hypertension; BML: both mitral leaflets; LAAO: left atrial appendage occlusion.

Table 2: Mitral valve and TV pathologies

	All MVR patients *N* = 1000	3D *N* = 484	Loops *N* = 347	CT *N* = 221
MV stenosis, *n* (%)				
None	953 (95.30)	463 (95.66)	334 (96.25)	210 (95.02)
Mild	13 (1.30)	6 (1.24)	5 (1.44)	4 (1.81)
Moderate	10 (1.00)	3 (0.62)	2 (0.58)	2 (0.90)
Severe	24 (2.40)	12 (2.48)	6 (1.73)	5 (2.26)
MV regurgitation, *n* (%)				
Mild	13 (1.30)	7 (1.45)	4 (1.15)	3 (1.36)
Moderate	13 (1.30)	9 (1.86)	8 (2.31)	6 (2.71)
Severe	974 (97.40)	468 (96.69)	335 (96.54)	212 (95.93)
Carpentier classification, *n* (%)				
I	114 (11.40)	45 (9.30)	37 (10.66)	16 (7.24)
II	764 (76.40)	392 (80.99)	281 (80.98)	185 (83.71)
IIIa	99 (9.90)	36 (7.44)	22 (6.34)	13 (5.88)
IIIb	23 (2.30)	11 (2.27)	7 (2.02)	7 (3.17)
MV disease aetiology, *n* (%)				
Degenerative	756 (75.60)	390 (80.58)	278 (80.12)	182 (82.35)
Functional	136 (13.60)	55 (11.36)	43 (12.39)	23 (10.41)
Rheumatic	97 (9.70)	35 (7.23)	22 (6.34)	13 (5.88)
Endocarditis	11 (1.10)	4 (0.83)	4 (1.15)	3 (1.36)
MV prolapse, *n* (%)				
0	240 (24.00)	90 (18.60)	64 (18.44)	34 (15.38)
AML	121 (12.10)	48 (9.92)	34 (9.80)	27 (12.22)
PML	517 (51.70)	277 (57.23)	194 (55.91)	130 (58.82)
BML	122 (12.20)	69 (14.26)	55 (15.85)	30 (13.57)
TV regurgitation, *n* (%)				
None	327 (32.70)	132 (27.27)	99 (28.53)	57 (25.79)
Mild	25 (2.50)	25 (5.17)	25 (7.20)	25 (11.31)
Moderate	645 (64.50)	325 (67.15)	221 (63.69)	137 (61.99)
Severe	3 (0.30)	2 (0.41)	2 (0.58)	2 (0.90)
TV annular dilatation	141 (14.10)	50 (10.33)	34 (9.80)	21 (9.50)

MV: mitral valve.

present in 12.1% of the patients, 51.7% had a PML prolapse and 12.2% a bileaflet prolapse. At least mild TV regurgitation was present in 67.2% of the patients and 14.1% exhibited dilatation of the TV annulus (Table 2).

59.6% were operated under 2D video assistance, 40.1% of the patients were operated fully endoscopic via 3D scope. The femoral artery was used for arterial cannulation site in 97.5% patients, 2% were cannulated via the axillary artery, very few patients were cannulated via the carotid artery or the ascending aorta. 20.8% received an additional cannula into the jugular vein. St. Thomas cardioplegia supplemented with blood was used in 79.9% of the patients, 18.1% received Custodiol cardioplegia. MV repair was achieved in 90% of the patients, MV replacement by a bioprosthesis was performed in 6.8% and 3.2% received a mechanical prosthesis. 12.5% had MV repair on the AML, 52.5% on the PML and 12.5% received bileaflet repair. Leaflet resection was performed in 25% of the patients and 3.8% underwent sliding plasty. In 54.7%, artificial chords were used for MV repair. The TV was repaired in 20.8% and 14.5% underwent concomitant AF surgery. Left arterial appendage was occluded in 16.8% of the patients (Table 3).

Technical success was achieved in 936 patients (93.6%). There was no difference in the success rate of MV repair irrespective of underlying MV pathology (Supplementary Material, Table S1). Intraoperative SAM was present in 15 patients (1.5%), and 28 patients underwent conversion to sternotomy (2.8%). Conversion to MV replacement was performed in 14 patients (1.4%), rethoracotomy for bleeding in 54 patients (5.4%). Five patients had a perioperative myocardial infarction (0.5%), and 2 patients had a perioperative stroke (0.2%). Ten patients died perioperatively (1%), 5 of which were non-cardiac. Five patients died due to cardiac reasons (3 cardiogenic shock, 1 acute valve thrombosis with fatal stroke, 1 intraoperative pulmonary haemorrhage).

3D endoscopy improved cross-clamp (X-clamp) time (before: 116.9 ± 38.2, after: 109.7 ± 35.1, $P = 0.002$). The use of loops improved both cardiopulmonary bypass (CPB) time (before: 206.5 ± 62.5, after: 195.2 ± 55, $P = 0.003$) and X-clamp time (before: 117.2 ± 38.1, after: 106.4 ± 33.6, $P < 0.001$). The introduction of preoperative CT scans had no impact on periprocedural safety or success but improved CPB time (before: 206.6 ± 61.1, after: 188.5 ± 55.0, $P < 0.001$) and X-clamp time (before: 116.5 ± 37.1, after: 102.7 ± 34.0, $P < 0.001$) (Table 4).

DISCUSSION

The aim of this study was to identify the impact of era and technical improvements on perioperative outcome after MIMVS. We have analysed a consecutive series of 1000 patients operated at our centre between 2001 and 2020. Perioperative survival was 99.1%, and periprocedural success 93.5% with a periprocedural safety of 96.3%. Significant improvement in periprocedural safety attributed to the lower rates of postoperative low output and less reoperations for bleeding. There was no influence on periprocedural success. The introduction of 3D visualization improved X-clamp but not CPB times. The use of loops and preoperative

Table 3: Surgical procedure

	All MVR patients *N* = 1000	3D *N* = 484	Loops *N* = 347	CT *N* = 221
Arterial cannulation site, *n* (%)				
Ascending aorta	2 (0.20)	1 (0.21)	0 (0.00)	0 (0.00)
Femoral artery	975 (97.50)	470 (97.11)	339 (97.69)	215 (97.29)
Axillary artery	20 (2.00)	10 (2.07)	5 (1.44)	3 (1.36)
Other	3 (0.30)	3 (0.62)	3 (0.86)	3 (1.36)
Venous cannulation site, *n* (%)				
Femoral vein	789 (78.90)	405 (83.68)	292 (84.15)	181 (81.90)
Femoral and jugular vein	208 (20.80)	79 (16.32)	55 (15.85)	40 (18.10)
Other	3 (0.30)	0 (0.00)	0 (0.00)	0 (0.00)
Cardioplegia type, *n* (%)				
None	20 (2.00)	10 (2.07)	8 (2.31)	4 (1.81)
St. Thomas	799 (79.90)	369 (76.24)	241 (69.45)	133 (60.18)
Custodiol	181 (18.10)	105 (21.69)	98 (28.24)	84 (38.01)
MV replacement, *n* (%)				
None	900 (90.00)	445 (91.94)	323 (93.08)	207 (93.67)
Biological	68 (6.80)	26 (5.37)	15 (4.32)	8 (3.62)
Mechanical	32 (3.20)	13 (2.69)	9 (2.59)	6 (2.71)
MV resection, *n* (%)				
None	750 (75.00)	416 (85.95)	319 (91.93)	211 (95.48)
AML	8 (0.80)	2 (0.41)	2 (0.58)	1 (0.45)
PML	234 (23.40)	62 (12.81)	23 (6.63)	7 (3.17)
BML	8 (0.80)	4 (0.83)	3 (0.86)	2 (0.90)
Artificial chords, *n* (%)				
None	453 (45.30)	157 (32.44)	101 (29.11)	61 (27.60)
AML	113 (11.30)	55 (11.36)	37 (10.66)	26 (11.76)
PML	361 (36.10)	232 (47.93)	176 (50.72)	117 (52.94)
AML + PML	73 (7.30)	40 (8.26)	33 (9.51)	17 (7.69)
Concomitant TV surgery	208 (20.80)	79 (16.32)	55 (15.85)	40 (18.10)
aFib surgery	145 (14.50)	60 (12.40)	43 (12.39)	27 (12.22)
LAAO, *n* (%)				
Suture	127 (12.70)	29 (5.99)	12 (3.46)	1 (0.45)
Clip	41 (4.10)	41 (8.47)	41 (11.82)	36 (16.29)

AML: anterior mitral leaflet; MV: mitral valve; PML: posterior mitral leaflet.

CT scan both had no impact on periprocedural success or safety but was associated with CPB and X-clamp times. The use of Custodiol potentially reduces the X-clamp and CPB times. In contrast to the described 3 technical advancements, Custodiol was used throughout the whole investigation period, albeit more common in later years. When testing for Custodiol as an interaction, X-clamp and CPB times significantly correlate with the additions of technical advancements (Supplementary Material, Table S1).

Our results show that increased surgical experience improves safety in MIMVS. Our program was established in 2001, and expertise was ever-growing since, concomitant with improved operative outcomes. Besides experience, 3 major technical additions were added over the years. In 2008, loop technique was introduced. The paradigm of leaflet preservation rather than resection has been postulated in the last years, although recent data of a randomized, controlled trial could not confirm superiority over leaflet resection in terms of transmitral gradients or rates of regurgitation 12 months after surgery at peak exercise [14]. However, another randomized trial found the loop technique superior to leaflet resection in terms of leaflet coaptation length, possibly resulting in a more durable MV repair [20]. The technique is easy to learn and feasible in a MIMVS setting.

In 2018, preoperative CT scan of every patient undergoing MIMVS was introduced. A recent meta-analysis reviewing 57 studies including 13 731 patients concluded that systematic preoperative CT screening is associated with improved outcomes regarding stroke, need for dialysis and a trend towards lower operative mortality after MIMVS [21]. Besides preoperative orientation of anatomical features and pitfalls like calcifications, preoperative CT scans might be a valuable tool to identify patients eligible for MIMVS [23]. Patients with femoral kinking or calcifications are at higher risk for complications during MIMVS, so are patients with severe calcifications of the mitral leaflets or annulus. There are techniques available to deal with femoral kinking or calcification during femoral cannulation, including the use of stiffer guide wires and the use of fluoroscopy [24]. The repair of calcified MV leaflets can be achieved via, e.g. triangular resection. However, both conditions are associated with increased operative risk and operative times. These patients can be identified and precluded from a lateral minithoracotomy approach and operated via hemisternotomy.

Automated fasteners have proven useful and safe in MIMVS and contribute to reduced operative times [25, 26]. In our centre, automated fasteners were used in all patients with an indication to mitral replacement, and selected patients who have an expectation for longer operative times (e.g. concomitant tricuspid valve repair, left atrial ablation and LAA occlusion). In this study, we have not investigated the impact of automatic fasteners on operative times in our cohort; however, this should be elucidated in future trials.

The use of preoperative CT was associated with improved operative times in our cohort. This might be due to the fact that patients who might need longer operative times due to

Table 4: Impact of technical improvements

	All N = 1000	Before 3D N = 516	After 3D N = 484	P-Value	Before Loops N = 653	After Loops N = 347	P-Value	Before CT N = 779	After CT N = 221	P-Value
Technical success, n (%)	936 (93.60)	479 (92.83)	457 (94.42)	0.369	604 (92.50)	332 (95.68)	0.069	727 (93.32)	209 (94.57)	0.609
CPB time, mean (SD)	202.57 (60.24)	205.03 (61.48)	199.95 (58.85)	0.183	206.52 (62.54)	195.15 (55.00)	0.003	206.57 (61.06)	188.48 (55.14)	<0.001
X-clamp time, mean (SD)	113.42 (36.89)	116.91 (38.22)	109.70 (35.08)	0.002	117.17 (38.05)	106.38 (33.54)	<0.001	116.52 (37.13)	102.67 (34.02)	<0.001
Ventilation time, mean (SD)	21.97 (73.25)	19.27 (56.40)	24.86 (87.69)	0.234	21.98 (71.95)	21.96 (75.74)	0.997	21.65 (69.52)	23.10 (85.29)	0.817
Second X-clamp, n (%)	38 (3.80)	23 (4.46)	15 (3.10)	0.339	28 (4.29)	10 (2.88)	0.351	30 (3.85)	8 (3.62)	1.000
Intraoperative SAM, n (%)	15 (1.50)	9 (1.74)	6 (1.24)	0.692	12 (1.84)	3 (0.86)	0.351	14 (1.80)	1 (0.45)	0.213
CX occlusion, n (%)	2 (0.20)	1 (0.19)	1 (0.21)	1.000	1 (0.15)	1 (0.29)	1.000	1 (0.13)	1 (0.45)	0.393
Conversion: sternotomy, n (%)	28 (2.80)	14 (2.71)	14 (2.89)	1.000	19 (2.91)	9 (2.59)	0.931	22 (2.82)	6 (2.71)	1.000
Conversion: MV replacement, n (%)	14 (1.40)	7 (1.36)	7 (1.45)	1.000	11 (1.68)	3 (0.86)	0.401	13 (1.67)	1 (0.45)	0.326
Rethoracotomy for bleeding, n (%)	54 (5.40)	28 (5.43)	26 (5.37)	1.000	42 (6.43)	12 (3.46)	0.067	52 (6.68)	2 (0.90)	0.001
Reoperation for valve dysfunction <30 days, n (%)	8 (0.80)	4 (0.78)	4 (0.83)	1.000	6 (0.92)	2 (0.58)	0.721	6 (0.77)	2 (0.90)	0.692
Myocardial infarction, n (%)	5 (0.50)	3 (0.58)	2 (0.41)	1.000	3 (0.46)	2 (0.58)	1.000	4 (0.51)	1 (0.45)	1.000
Stroke, n (%)	2 (0.20)	0 (0.00)	2 (0.41)	0.234	1 (0.15)	1 (0.29)	1.000	2 (0.26)	0 (0.00)	1.000
Low output, n (%)	23 (2.30)	8 (1.55)	15 (3.10)	0.155	14 (2.14)	9 (2.59)	0.818	18 (2.31)	5 (2.26)	1.000
Mortality, n (%)	10 (1.00)	7 (1.36)	3 (0.62)	0.344	9 (1.38)	1 (0.29)	0.178	10 (1.28)	0 (0.00)	0.129

CPB: cardiopulmonary bypass; MV: mitral valve; SD: standard deviation; X-clamp: cross-clamp; SAM: systolic anterior motion; Cx: circumflex artery.

underlying conditions are excluded from MIMVS surgery by CT scan and operated by a hemi-sternotomy approach at our centre. Thus, preoperative CT scans might objectify clinical experience and empirical decision-making. In our patient cohort, the use preoperative CT scans did not decrease perioperative complications. A larger cohort including more high-risk patients might be necessary to unmask this possible effect. Besides patient selection and intervention planning, high-resolution CT imaging (e.g. 4D CT) might be helpful to elucidate complex MV pathologies and their haemodynamic relevance and thus, be a valuable adjunctive tool to plan mitral repair strategies [27].

3D endoscopy was introduced in 2014 at our institution. The 3D technology provides a realistic view of the surgical field and the MV pathology. Moreover, surgical manipulation in a three-dimensional environment feels more intuitive for operating surgeons. This might reduce the learning curve and lead to faster operative times [28]. Recently, developed high-fidelity MIMVS simulators might be a valuable tool to further reduce the intraoperative learning curve and to prepare surgeons to start operating endoscopically [29].

Limitations

This is a retrospective observational study with all limitations that are associated with it including confounding and bias. During the advancement of specialized program, patients gradually benefit from added techniques The aim of this study is to show the overall improvement in outcomes by improving patient pathways and implementing technical advancements into a clinical program. Impacts of specific measurements on clinical outcomes are only descriptive. To determine the distinct effects of a single measure, randomized controlled trials would be unavoidable.

Altogether, our data suggest that (i) surgical experience and (ii) technical improvements are related to increased operative success and decreased operative times in patients undergoing MIMVS.

SUPPLEMENTARY MATERIAL

Supplementary material is available at *ICVTS* online.

Funding

This study was covered by the Department of Cardiac Surgery, Medical University of Innsbruck.

Conflict of interest: NB Speaker's Honoraria: Edwards Lifesciences, Medtronic. Research Grant: Edwards Lifesciences, Corcym.

DATA AVAILABILITY

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

Author contributions

Can Gollmann-Tepeköylü: Conceptualization; Data curation; Investigation; Writing—original draft. **Daniel Höfer:** Data curation; Validation; Writing—review & editing. **Johannes Holfeld:** Data curation; Investigation; Writing—review & editing. **Felix Nägele:** Data curation; Software; Writing—original draft. **Jakob Hirsch:** Data curation; Methodology; Writing—review & editing. **Cenk Ulvi Oezpeker:** Data curation; Methodology; Writing—review & editing. **Elfriede Ruttmann-Ulmer:** Methodology; Writing—review & editing. **Juliane Kilo:** Data curation; Methodology; Supervision. **Herbert Hangler:** Data curation; Investigation; Methodology. **Ludwig Müller:** Conceptualization; Data curation; Project administration; Supervision; Validation; Writing—review & editing. **Michael Grimm:** Conceptualization; Project administration; Supervision; Validation; Writing—review & editing. **Nikolaos Bonaros:** Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Supervision; Writing—original draft.

Reviewer information

Interdisciplinary CardioVascular and Thoracic Surgery thanks Roman Gottardi, Tomislav Kopjar and the other anonymous reviewer(s) for their contribution to the peer review process of this article.

REFERENCES

[1] Vahanian A, Beyersdorf F, Praz F, Milojevic M, Baldus S, Bauersachs J *et al.* 2021 ESC/EACTS Guidelines for the management of valvular heart disease. Eur Heart J 2021; 43:561–632.

[2] Bonaros N, Höfer D, Grimm M, Müller L. How to define minimally invasive mitral surgery? First, by a fast-track procedure. Eur J Cardiothorac Surg 2022;62(5):ezac512.

[3] Vollroth M, Seeburger J, Garbade J, Pfannmueller B, Holzhey D, Misfeld M *et al.* Minimally invasive mitral valve surgery is a very safe procedure with very low rates of conversion to full sternotomy. Eur J Cardiothorac Surg 2012;42:e13–5; discusson–e16.

[4] Ko K, de Kroon TL, Post MC, Kelder JC, Schut KF, Saouti N *et al.* Minimally invasive mitral valve surgery: a systematic safety analysis. Open Heart 2020;7(2):e001393.

[5] Li M, Zhang J, Gan TJ, Qin G, Wang L, Zhu M *et al.* Enhanced recovery after surgery pathway for patients undergoing cardiac surgery: a randomized clinical trial. Eur J Cardiothorac Surg 2018;54:491–7.

[6] Seeburger J, Borger MA, Doll N, Walther T, Passage J, Falk V *et al.* Comparison of outcomes of minimally invasive mitral valve surgery for posterior, anterior and bileaflet prolapse. Eur J Cardiothorac Surg 2009; 36:532–8.

[7] Ben Zekry S, Spiegelstein D, Sternik L, Lev I, Kogan A, Kuperstein R *et al.* Simple repair approach for mitral regurgitation in Barlow disease. J Thorac Cardiovasc Surg 2015;150:1071–7.e1.

[8] David TE, David CM, Tsang W, Lafreniere-Roula M, Manlhiot C. Long-term results of mitral valve repair for regurgitation due to leaflet prolapse. J Am Coll Cardiol 2019;74:1044–53.

[9] Feirer N, Kornyeva A, Lang M, Sideris K, Voss B, Krane M *et al.* Non-robotic minimally invasive mitral valve repair: a 20-year single-centre experience. Eur J Cardiothorac Surg 2022;62(5):ezac223.

[10] Van Praet KM, Kofler M, Hirsch S, Akansel S, Hommel M, Sündermann SH *et al.* Factors associated with an unsuccessful fast-track course following minimally invasive surgical mitral valve repair. Eur J Cardiothorac Surg 2022;62(4):ezac451.

[11] Borger MA, Kaeding AF, Seeburger J, Melnitchouk S, Hoebartner M, Winkfein M *et al.* Minimally invasive mitral valve repair in Barlow's disease: early and long-term results. J Thorac Cardiovasc Surg 2014;148:1379–85.

[12] Cevasco M, Myers PO, Elbardissi AW, Cohn LH. Foldoplasty: a new and simplified technique for mitral valve repair that produces excellent medium-term outcomes. Ann Thorac Surg 2011;92:1634–7; discussion 37–8.

[13] Pfannmueller B, Misfeld M, Davierwala P, Weiss S, Borger MA. Concomitant tricuspid valve repair during minimally invasive mitral valve repair. Thorac Cardiovasc Surg 2020;68:486–91.

[14] Chan V, Mazer CD, Ali FM, Quan A, Ruel M, de Varennes BE *et al.* Randomized, controlled trial comparing mitral valve repair with leaflet resection versus leaflet preservation on functional mitral stenosis: the CAMRA CardioLink-2 study. Circulation 2020;142:1342–50.

[15] Johnston DR, Gillinov AM, Blackstone EH, Griffin B, Stewart W, Sabik JF 3rd *et al*. Surgical repair of posterior mitral valve prolapse: implications for guidelines and percutaneous repair. Ann Thorac Surg 2010;89:1385–94.
[16] Müller L, Bonaros N. Surgical mitral valve repair is unbeaten also in the elderly. Eur J Cardiothorac Surg 2022;62(2):ezac353.
[17] Krapf C, Wohlrab P, Häußinger S, Schachner T, Hangler H, Grimm M et al Remote access perfusion for minimally invasive cardiac surgery: to clamp or to inflate? Eur J Cardiothorac Surg 2013;44:898–904.
[18] Murzi M, Cerillo AG, Miceli A, Bevilacqua S, Kallushi E, Farneti P *et al.* Antegrade and retrograde arterial perfusion strategy in minimally invasive mitral-valve surgery: a propensity score analysis on 1280 patients. Eur J Cardiothorac Surg 2013;43:e167–e172.
[19] Ito T, Hosoba S, Orii M, Kato R. Minimally invasive valve surgery using high resolution (3D) scope. Oper Tech Thorac Cardiovasc Surg 2021;25: 574–587.
[20] Falk V, Seeburger J, Czesla M, Borger MA, Willige J, Kuntze T *et al*. How does the use of polytetrafluoroethylene neochordae for posterior mitral valve prolapse (loop technique) compare with leaflet resection? A prospective randomized trial. J Thorac Cardiovasc Surg 2008;136:1205; discussion 1205–6.
[21] Leonard JR, Henry M, Rahouma M, Khan FM, Wingo M, Hameed I *et al.* Systematic preoperative CT scan is associated with reduced risk of stroke in minimally invasive mitral valve surgery: a meta-analysis. Int J Cardiol 2019;278:300–6.
[22] Bonaros N, Hoefer D, Oezpeker C, Gollmann-Tepeköylü C, Holfeld J, Dumfarth J *et al.* Predictors of safety and success in minimally invasive surgery for degenerative mitral disease. Eur J Cardiothorac Surg 2022;61: 637–44.
[23] Abu-Omar Y, Fazmin IT, Ali JM, Pelletier MP. Minimally invasive mitral valve surgery. J Thorac Dis 2021;13:1960–70.
[24] Bangalore S, Bhatt DL. Femoral arterial access and closure. Circulation 2011;124:e147–e56 .
[25] Grapow MTR, Mytsyk M, Fassl J, Etter P, Matt P, Eckstein FS *et al.* Automated fastener versus manually tied knots in minimally invasive mitral valve repair: impact on operation time and short- term results. J Cardiothorac Surg 2015;10:146.
[26] Salmasi MY, Chien L, Hartley P, Al-Balah A, Lall K, Oo A *et al*. What is the safety and efficacy of the use of automated fastener in heart valve surgery? J Card Surg 2019;34:1598–607.
[27] Loghin C, Loghin A. Role of imaging in novel mitral technologies—echocardiography and computed tomography. Ann Cardiothorac Surg 2018; 7:799–811.
[28] Maselli D, Nardella S, Santise G, Iavazzo A, Chiariello L. Micro-invasive 3D endoscopic mitral valve surgery. Surg Technol Int 2022;40:227–234.
[29] Sardari Nia P, Heuts S, Daemen JHT, Olsthoorn JR, Chitwood WR Jr, Maessen JG. The EACTS simulation-based training course for endoscopic mitral valve repair: an air-pilot training concept in action. Interact CardioVasc Thorac Surg 2020;30:691–8.