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Minimally invasive cardiac surgery: State of the art and current challenges

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Minimally invasive cardiac surgery: State of the art and current challenges

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Editorial: Minimally invasive cardiac surgery: state of the art and current challenges

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Editorial on the Research Topic
Minimally invasive cardiac surgery: State of the art and current challenges

Minimally invasive cardiac surgery (MICS) has undergone a rapid evolution over the past three decades due to the significant progress in the development of emerging technologies and improved surgical techniques in the cardiovascular field.

Only about one-third of all cardiac surgery procedures are currently performed via small skin incisions (minithoracotomy and ministernotomy). However, the invasiveness of any cardiosurgical procedure cannot only be defined by access (skin incision) but also by the use of cardiopulmonary bypass with potential cardiac arrest and heart valve repair or valve-sparing operation (1). This positive trend continues to evolve, notably with the development of increasingly efficient endoscopic, robotic, and transcatheter procedures (2–4).

Driven by reduced surgical trauma, blood loss, pain, and hospital stay, as well as better cosmesis and quality of life, the considerable attention gained through the application of MICS is attributable to improved postoperative outcomes (5–8). However, some concerns remain with the technical challenges and the consequent prolonged intraoperative durations and risks of vascular complications, including thromboembolism, as well as associated neurological complications (9).

With this Research Topic, we aim to provide readers, clinicians, researchers, and developers a broad scientific and technological overview of the progress made with the various innovative minimally invasive surgical, reconstructive, and interventional approaches to coronary arteries, heart valves, and aortas, since their introduction about 30 years ago.

An excellent didactic summary of 10 years of experience with MICS, especially endoscopic, incorporating seven lessons learned is provided by Ahmad et al. Based on their broad experience, the authors suggest MICS can be safely, effectively, and reproducibly performed by a wide range of surgeons. Additionally, it can serve as a good template for establishing MICS and accelerating the learning curve while improving patient outcomes. From the same two institutions, an interesting overview about the experience with minimally invasive direct coronary artery bypass grafting (MIDCAB) is published by Monsefi et al.. The authors present the short-term results of 234 patients undergoing MIDCAB between 2017 and 2021 with a 30-day mortality of 1.7%. This study

confirms the aforementioned fact that the recently started MICS programme can offer very good outcomes to patients. These short-term results are even comparable with the largest ever published MIDCAB cohort (10).

The gold standard treatment of primary degenerative mitral valve insufficiency is surgical valve repair, which nowadays is performed predominantly in MICS and increasingly in three-dimensional endoscopic fashion (2). Elderly patients suffering from additional atherosclerosis bear an increased risk due to retrograde arterial perfusion. Selective cannulation of the right axillary artery and herewith antegrade perfusion may be of benefit. Petersen et al. performed a study comparing short-term outcomes of this perfusion strategy with standard retrograde femoral perfusion. They conclude that patients with a higher perioperative risk and severe atherosclerosis would benefit from antegrade axillary perfusion.

Since its introduction in 1992, aortic valve (AV) reimplantation (David procedure) has become the standard technique for patients suffering from aortic root aneurysm with or without AV insufficiency and has produced excellent short- and long-term results (11). A quarter century experience with this valve-sparing operation from a teaching centre is reported by Sromicki et al. The 30-day mortality of their cohort of 131 patients was 2%. Freedom from reoperation at 5 and 10 years was 93.5% ± 2.4% and 87.0% ± 3.5%, respectively. These results are comparable with other mid-volume centres (12); however, they are not as exceptional as the results from the Toronto group. In our opinion, the explanation for these exceptional and almost unreproducible results is the extreme selection of patients over the increasing course of time.

Adding a minimal access to the aortic valve-sparing, this procedure can be then considered as a great representative of MICS and is of major benefit to the patients. Shrestha et al. compared patients undergoing elective isolated David procedure via ministernotomy (42 patients) with full sternotomy (220 patients). Despite the fact that perioperative outcomes (cardio-pulmonary bypass and aortic cross-clamp time) were statistically relevantly shorter in the full sternotomy group, no difference was found in short- and long-term postoperative outcomes, including valve performance.

The MICS has not yet been adopted in aortic arch repair and even less in the surgery of acute type A aortic dissection (13). Since January 2019, Xie et al. have operated all obese (BMI $\geq$30 kg/m^2) patients with acute type A aortic dissection using a self-made triple-branched stent-graft for total arch replacement via partial upper sternotomy. In their study, 35 patients underwent full sternotomy, and 30 partial upper sternotomy. The latter strategy was proved to be safe, effective, and superior to full sternotomy in terms of blood loss, postoperative blood transfusion, and respiratory complications.

The Research Topic was rounded off by three interesting case reports. Pojar et al. present a remarkable case of successful robotic repair of unroofed coronary sinus, which was accomplished using an excellent high-resolution video. Salamate et al. publish an extraordinary technically challenging case of video-assisted minimally invasive mitral and pulmonary valve replacement as a reoperation in a patient with situs invs. totalis. This case report was also accomplished using an excellent high-resolution video. Finally, Wu et al. present a remarkable case of successful minimally invasive bicuspid AV repair through right-anterior minithoracotomy.

The aim of this Research Topic was to assess current progress in MICS of the coronary arteries, heart valves, and aorta. Nine papers were accepted and collected in this Research Topic, and to date, have been seen by over 7,500 readers. These publications confirm the steady progress of this approach and demonstrate that MICS is safe and feasible. However, MICS is still relatively uncommon, being confined mainly to specialist centres. In our opinion, MICS is the approach of the future and is *a priori* suitable for every patient and every pathology; nevertheless, precise selection and rigorous preoperative planning are essential. More in-depth analyses on larger groups are also required.

Author contributions

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Conflict of interest

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Case report: Robotic repair of unroofed coronary sinus

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Unroofed coronary sinus is a rare congenital heart disease caused by the partial or complete absence of the common wall between the coronary sinus and left atrium. When indicated for repair, it is done either percutaneously or surgically. Repair using a totally endoscopic robotic procedure is rarely performed nor reported in the literature. We report a case of a 47-year-old male who underwent a successful totally endoscopic robotic repair of this anomaly.

KEYWORDS

robotic surgery, unroofed coronary sinus, cardiac surgery, minimally invasive surgery, congenital heart disease

Introduction

Unroofed coronary sinus is a rare congenital heart disease caused by the partial or complete absence of the common wall between the coronary sinus and left atrium (1). When indicated for surgical repair, it is generally done using median sternotomy or thoracotomy. Robotic surgery has been shown to be a feasible approach to repair (2). We present a case of a successful totally endoscopic robotic repair of this anomaly in an adult using the da Vinci Xi robotic system (Intuitive Surgical, Inc., Sunnyvale, CA, United States).

Case description

A 47-year-old male with arterial hypertension and with unroofed coronary sinus syndrome diagnosed two years before the surgery on transesophageal echocardiography (TEE) (**Figures 1**, **2**) and cardiac computed tomography (**Figures 3A,B**) was referred to our clinic for repair. He presented with progression of breathlessness on exertion for the last three months. There were no significant comorbidities. Preoperative TEE revealed dilated and overloaded right ventricle, dilated right atrium and coronary sinus,

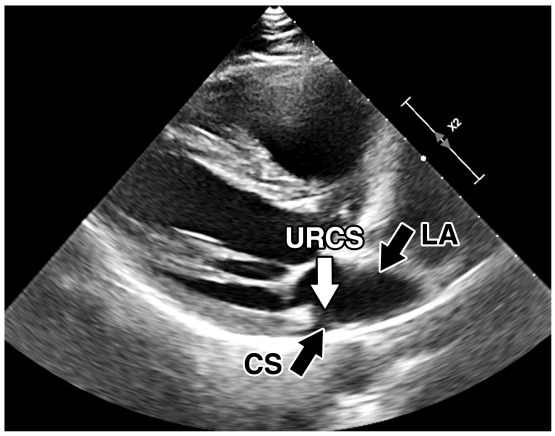

FIGURE 1
Preoperative transthoracic echocardiography. Preoperative transthoracic echocardiography images of the unroofed coronary sinus. Direct communication between the coronary sinus and left atrium. CS, coronary sinus; LA, left atrium; URCS, unroofed coronary sinus.

and mild tricuspid regurgitation. TEE demonstrated a direct communication between the left atrium and coronary sinus with left-to-right shunt flow shown by color Doppler imaging. No atrial septal defect was seen, persistent left superior vena cava was excluded as well. Systolic pulmonary artery pressure was estimated to be 40 mmHg based on tricuspid regurgitation. Left and right ventricle function was preserved. All pulmonary veins drained into the left atrium. There was no associated heart pathology. TEE and CT visualized the defect of the roof of the coronary sinus measuring 10 mm × 12 mm. Cardiac catheterization revealed the left-to-right shunt with a Qp/Qs ratio of 1.9:1, and selective coronary angiography confirmed normal coronary arteries. The European System for Cardiac Operative Risk Evaluation (EuroScore II) was calculated to be 0.7. After careful analysis of the case and thorough discussion with the patient, we decided on a robotically assisted repair of the defect. This was due to low comorbidities and optimal anatomical proportions for a minimally invasive surgical approach. Interventional approach with an occluder was rejected due to proximity of the defect to the interatrial septum and mitral valve leaflet.

Under general anesthesia with double-lumen intubation and after systemic heparinization, cardiopulmonary bypass was routinely established by right internal jugular vein and right femoral vessel cannulation. The da Vinci Xi robotic surgery system (Intuitive Surgical, Inc., Sunnyvale, CA, USA) was used. Robotic ports were introduced into the right hemithorax. A 30° endoscope was inserted through the third intercostal space. Two additional instrument ports in the second and fifth intercostal space. The atrial retractor was introduced through the fifth intercostal space anteriorly. Shortly after initiating extracorporeal circulation, the ascending aorta was cross-clamped and antegrade cardioplegia (Del Nido) was used to arrest the heart in the diastole. Left atriotomy was performed. Left atrium inspection did not reveal atrial septal defect. In agreement with the TEE findings, the unroofed CS was spotted in proximity to the posterior leaflet section (P3) of the mitral valve, circular with an area of about 15 mm × 15 mm (**Figures 4A,B** and **Supplementary Video 1**). As there was sufficient tissue around the defect, we performed direct continuous suture in two layers. The atrial septum was checked for any other defects, and atrial septal defect was excluded. The CS was checked for patency. After filling the right atrium and CS, we confirmed that there was no blood cardioplegia leakage through the sutures from the repaired roof of the CS to the left atrium. This was also verified by postoperative TEE. The left atriotomy was closed, the heart de-aired, and the cross-clamp released after 57 min with spontaneous renewal of heart contractions. Perioperative TEE confirmed an excellent result of the repair with no residual defects detected. The patient was then weaned from CPB.

Patient was extubated 7 h postoperatively. After 22 h in the ICU without any complications, the patient was transferred to the standard care unit. The patient's postoperative course was uneventful and he was discharged home 6 days after surgery without any residual shunt or new pathologies shown by postoperative transthoracic echocardiography.

Discussion

Unroofed coronary sinus syndrome (URCS) is a rare congenital heart disease caused by the absence of part or

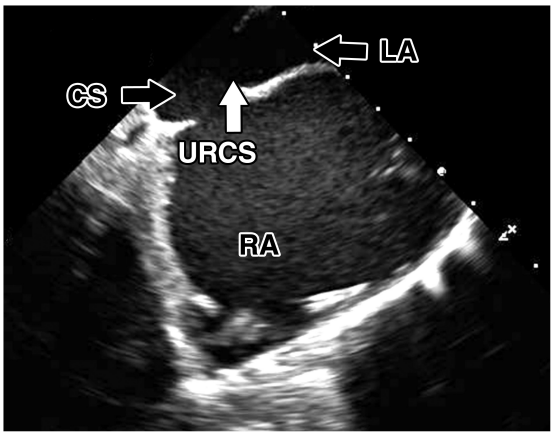

FIGURE 2
Preoperative transesophageal echocardiography. Preoperative transesophageal echocardiography images of the unroofed coronary sinus. Direct communication between the coronary sinus and left atrium. CS, coronary sinus; LA, left atrium; RA, right atrium; URCS, unroofed coronary sinus.

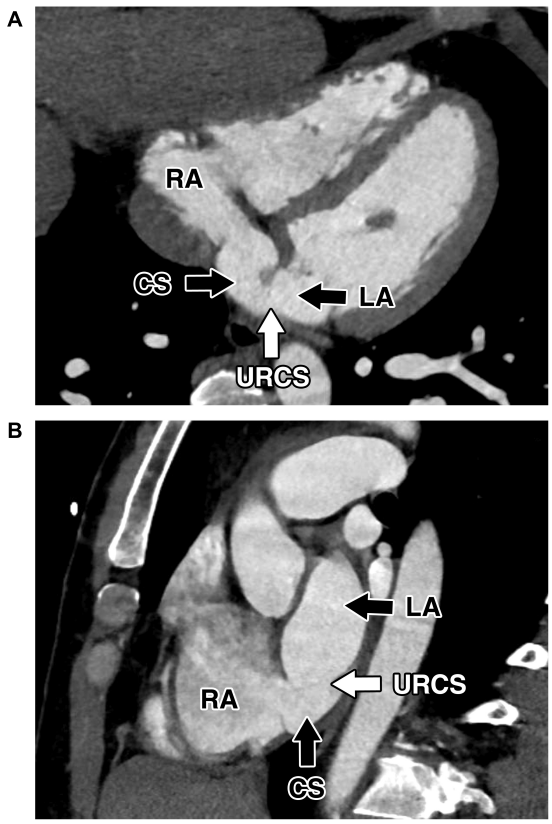

FIGURE 3
Preoperative cardiac computed tomography. Computed tomography showed extensive communication between the coronary sinus and left atrium caused by partial absence of the roof of the coronary sinus. The absence of the coronary sinus roof and communication between CS and the left atrium. **(A)** Modified four-chamber projection. **(B)** Modified short-axis projection. CS, coronary sinus; LA, left atrium; RA, right atrium; URCS, unroofed coronary sinus.

all of the common wall between the coronary sinus and left atrium (1). Raghib et al. were the first to describe the URCS in 1965 (3). It can be classified as type I, completely unroofed with Persistent Left Superior Vena Cava; type II, completely unroofed without PLSVC; type III partially unroofed midportion of the coronary sinus (as in the current case); and type IV, partially unroofed terminal portion of the coronary sinus (4).

Clinical manifestations of URCS are variable. Symptomatology ranges from long periods of being asymptomatic to classic clinical symptoms of right-sided heart overload. URCS may cause dyspnea on exertion or at rest, fatigue, tachypnoea, right ventricular failure, or cyanosis. When URCS is associated with persistent left superior vena cava, the patient may experience central cyanosis or paradoxical embolism and brain abscess (5).

Management of URCS is dependent on the severity of symptoms and associated pathologies, such as atrial septal defect or persistent left superior vena cava, and varies from conservative therapy to acute surgery. For large defects, and also if complications related to the right-to-left shunt occur, correction of URCS becomes a necessity. In case of small, usually asymptomatic defects, only regular follow-ups are recommended (5). In addition to defect size, associated heart pathologies are important for decision making regarding intervention indication.

As imaging tools, transthoracic echocardiography is the first step to evaluate patients with suspicion of URCS. Persistent left superior vena cava could be revealed by contrast echocardiography with an injection of bubble contrast into the left arm. In the presence of persistent left superior vena cava, the contrast will appear initially in the left atrium and subsequently in the right atrium (5). Currently TEE, especially three-dimensional echocardiography, computer tomography and magnetic resonance imaging are able to confirm the presence of such abnormalities, and offer precise

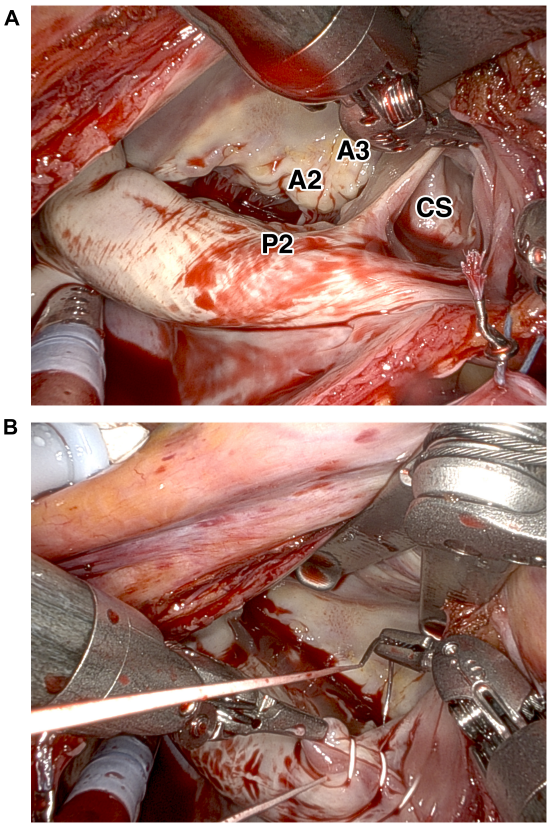

FIGURE 4
Intraoperative findings of the unroofed coronary sinus. Intraoperative findings showed **(A)** the unroofed portion of the coronary sinus at the left atrial side close to segment P3 of the posterior mitral leaflet. **(B)** Repair of the coronary sinus with direct continuous suture. A2, A2 segment of anterior mitral leaflet; A3, A3 segment of anterior mitral leaflet; P2, P2 segment of posterior mitral leaflet; CS, coronary sinus.

mapping of these structures. Prior to the therapy, cardiac catheterization and angiography have to be performed to clarify the anatomy. Special attention has to be paid to the presence of persistent left superior vena cava, a component of the Raghib syndrome, or other associated pathologies (3, 5, 6).

Treatment of URCS, if needed, involves closure of the defect causing a left-to-right shunting and correction of associated abnormalities. Classically, the treatment of URCS and persistent left superior vena cava, if needed, is surgical correction. URCS can be closed using a pericardial patch or direct sutures leaving the coronary sinus on the right and other abnormalities treated accordingly. Direct suture of the defect can be used assuming no tension is applied to the surrounding structures.

Approaches to the repair of an unroofed coronary sinus are variable. Surgical intervention is usually performed through median sternotomy. Minimally invasive approaches have been successfully employed to repair the defect. Handa et al. reported a case of a repair of a type III Unroofed coronary sinus using a right mini-thoracotomy with the aid of an endoscope (7). In their case visualization of the lesion could only be achieved with the aid of the endoscope guided by prior preoperative 3D TEE (2). Repair using robotic totally endoscopic procedure is rarely performed nor reported in the literature. Onan et al. performed and reported a successful totally endoscopic robotic repair of an unroofed CS proving the feasibility of this approach (2). Using the robotic system allows for effortless motion and better visualization. Compared to other minimally invasive approaches, robotic surgery provides quicker postoperative recovery and a better cosmetic outcome thanks to limited skin incisions. In our case, the unroofed CS was repaired successfully and safely using a total endoscopic robotic approach with an excellent postoperative outcome proving its efficacy and feasibility.

Recently, URCS can also be repaired percutaneously. Occluder devices can be employed in percutaneous procedures to close this defect with varying post-procedure complications (8). However, there are limitations for percutaneous procedure, regarding the diameter and relationship to surrounding structures.

In conclusion, unroofed coronary sinus is a rare but very important clinical problem. Robotic approach should be considered in similar cases in adult patients as it is a feasible alternative to conventional techniques.

Data availability statement

The original contributions presented in this study are included in the article/**Supplementary material**, further inquiries can be directed to the corresponding author.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements. Written informed consent was not obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

MP and ST wrote the manuscript. SC and MK contributed to the conceptualization and revised the manuscript. JV performed critical revision of the manuscript and approved the final version to be published. All authors contributed to the article and approved the submitted version.

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Author SC has a proctoring contract with Intuitive Surgical.

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Antegrade axillary arterial perfusion in 3D endoscopic minimally-invasive mitral valve surgery

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Background: Minimally-invasive (MIS) mitral valve (MV) surgery has become standard therapy in many cardiac surgery centers. While femoral arterial perfusion is the preferred cannulation strategy in MIS mitral valve surgery, retrograde arterial perfusion is known to be associated with an increased risk for cerebral atheroembolism, particularly in atherosclerosis patients. Therefore, antegrade perfusion may be beneficial in such cases. This analysis aimed to compare outcomes of antegrade axillary vs. retrograde femoral perfusion in the MIS mitral valve surgery.

Methods: This analysis includes 50 consecutive patients who underwent MIS between 2016 and 2020 using arterial cannulation of right axillary artery (Group A) due to severe aortic arteriosclerosis. Perioperative outcomes of the study group were compared with a historical control group of retrograde femoral perfusion (Group F) which was adjusted for age and gender (n = 50). Primary endpoint of the study was in-hospital mortality and perioperative cerebrovascular events.

Results: Patients in group A had a significantly higher perioperative risk as compared to Group F (EuroSCORE II: 3.9 ± 2.5 vs. 1.6 ± 1.5; p = 0.001; STS-Score: 2.1 ± 1.4 vs. 1.3 ± 0.6; p = 0.023). Cardiopulmonary bypass time (group A: 172 ± 46; group F: 178 ± 51 min; p = 0.627) and duration of surgery (group A: 260 ± 65; group F: 257 ± 69 min; p = 0.870) were similar. However, aortic cross clamp time was significantly shorter in group A as compared to group F (86 ± 20 vs. 111 ± 29 min, $p < 0.001$). There was no perioperative stroke in either groups. In-hospital mortality was similar in both groups (group A: 1 patient; group F: 0 patients; p = 0.289). In group A, one patient required central aortic repair due to intraoperative aortic dissection. No further cardiovascular events occurred in Group A patients.

Conclusion: Selective use of antegrade axillary artery perfusion in patients with systemic atherosclerosis shows similar in-hospital outcomes as compared to lower risk patients undergoing retrograde femoral perfusion. Patients with higher perioperative risk and severe atherosclerosis can be safely treated *via* the minimally invasive approach with antegrade axillary perfusion.

KEYWORDS

minimally-invasive surgery, mitral valve, antegrade perfusion, axillaris cannulation, mitral vale surgery

Introduction

Mitral Valve (MV) surgery has become the therapy of choice in severe MV disease and has been shown to result in low perioperative mortality and excellent long-term results (1). The introduction of minimally invasive (MIS) access in MV surgery has decreased surgical trauma and has resulted in faster postoperative recovery as well as higher patient satisfaction (1–3). While femoral arterial perfusion is the preferred cannulation strategy in MIS retrograde arterial perfusion is known to be associated with an increased complication risk in patients with atherosclerosis (4, 5). Therefore, antegrade perfusion may be beneficial in such situations. Different techniques have been proposed for antegrade perfusion during MIS. While Murzi et al. were able to show that antegrade direct cannulation of the aorta in MIC MV surgery resulted in a significant reduction of stroke and delirium (4, 6), a small cases series presented carotid artery cannulation for antegrade perfusion during MIC MV surgery (7). However, there are limited systematic reports regarding axillary artery cannulation for antegrade perfusion for MIS. This analysis aimed to compare postoperative outcomes of direct axillary artery perfusion in a consecutive cohort of patients with severe systemic atherosclerosis undergoing MIS and compare it to a control group of patients who had retrograde femoral perfusion.

Patients and methods

All patient data were anonymized and analyzed retrospectively. Formal consent from the patients was not obtained due to anonymity of the database. This analysis assessed perioperative outcomes of 50 consecutive patients who underwent MIS between July 2016 and January 2020 using a direct arterial cannulation of the right axillary artery (Group A). Perioperative outcomes of the study group were compared with a historical (January 2011–April 2018) age- and gender-adjusted control group of patients who had a retrograde femoral perfusion during MIS mitral valve surgery (Group F) (n = 50). Primary study endpoint was in-hospital mortality. Secondary endpoint was the rate of perioperative cerebrovascular events in both study groups.

Preoperative protocol for minimally-invasive surgery

In our institution, all patients presenting with severe MV disease (regurgitation or stenosis) are considered potential candidates for minimally-invasive access (**Figure 1**). If concomitant procedures necessitate median sternotomy access (e.g., coronary artery bypass graft, aortic valve replacement, replacement of the ascending aorta), the patient is scheduled for conventional sternotomy with a limited skin incision. In case of isolated mitral valve surgery (repair or replacement) as well as in need of simultaneous tricuspid valve repair, closure of left atrial appendage or surgical ablation, minimally invasive surgery is planned. In this setting we routinely use right anterolateral minithoracotomy with soft tissue retractor and 3D fully-endoscopic approach. In such patients (group A as well as group F), preoperative imaging includes a duplex evaluation of femoral and carotid vessels. If atheromatous plaques or a stenosis is present in the sonography, risk factors for arteriosclerosis are present or if the patient is $\geq$70 years, a native computed tomography (CT) scan of the thoracic and abdominal aorta is performed. With this systematic approach unnecessary radiation exposure in younger patients ($<$70 years) will be prevented. If there are no signs of arteriosclerosis a retrograde arterial perfusion is performed by direct cannulation of the arteria femoralis. In case of systemic arteriosclerosis in the thoracic or/and abdominal aorta in the CT scan (**Figure 2**), an antegrade arterial perfusion *via* axillary artery is performed (**Figure 3**).

Procedural steps of axillary artery cannulation

The procedural steps of axillary artery cannulation are outlined in **Supplementary Video 1**. Following a 3 cm

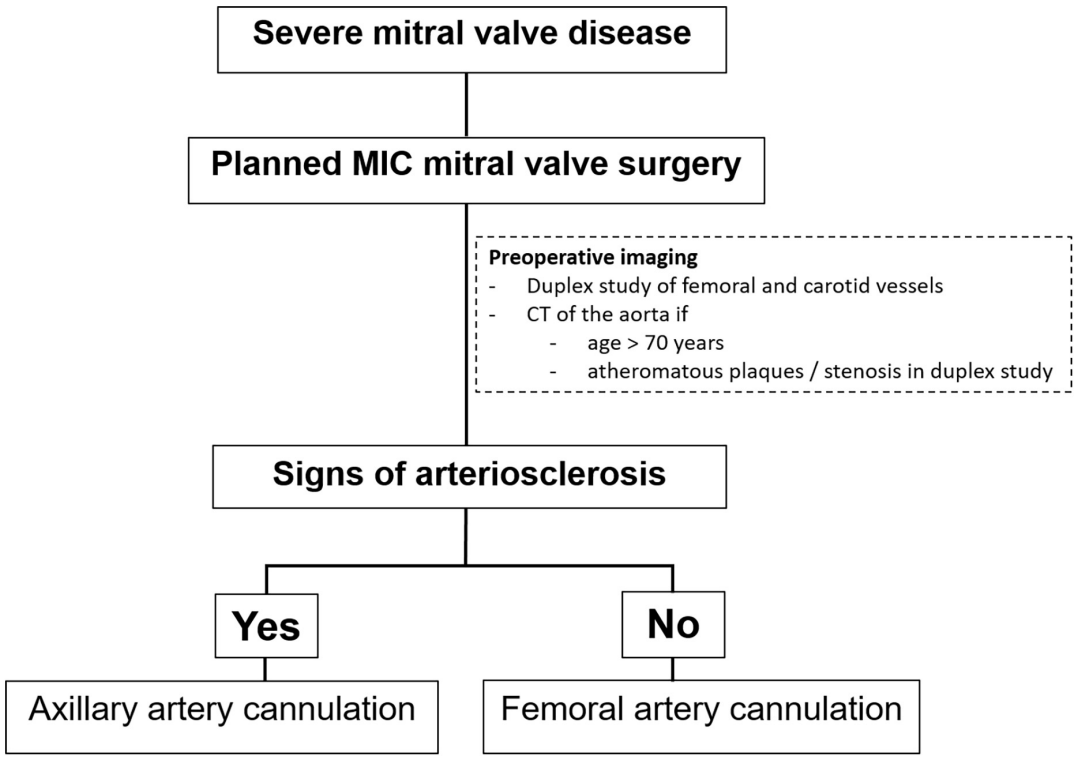

FIGURE 1
Treatment strategy at our institution in patients with severe mitral valve (MV) disease planned for a minimally-invasive (MIC) mitral valve surgery.

infraclavicular incision, the axillary artery is identified. After placement of cannlation sutures, direct puncture of the axillary artery is performed using Seldinger's technique. Echocardiographic visualization of the wire is crucial to avoid vascular injury. After placing the dilatator over the wire, a 5–8 mm incision of the axillary artery is performed. Afterward, the arterial cannula is carefully placed 1.5–2 cm into the vessel avoiding any resistance. Depending of the size of the axillary artery, we use a 18 Fr. or 20 Fr. short-tip Medtronic cannula. After fixation of the cannula, another stay suture is placed at the skin level to prevent dislocation of the cannula during cardiopulmonary bypass (CPB) perfusion.

Analysis of primary and secondary endpoints

Baseline and perioperative variables were collected retrospectively from our institutional electronic patient records and were entered into a standardized database. Intraoperative complications as well as in-hospital death were analyzed. Further postoperative complications such as neurovascular complications (e.g., stroke) or bleeding requiring redo surgery, pneumothorax, and access site complications (e.g., wound healing disorder, bleeding complications) were recorded.

Statistical analysis

Categorical variables are expressed as frequencies and percentages throughout the manuscript and comparisons were made using chi-square test or Fisher's exact test, as appropriate. Normally distributed continuous variables are presented as mean ± standard deviation. All reported *p*-values are two-sided and *p*-values of 0.05 or less were considered statistically significant. All statistical analyses were accomplished using Excel 16.21 (Microsoft, USA) and IBM SPSS 23 software (IBM Corp., New York, NY, USA).

Results

Preoperative characteristics

Preoperative characteristics of study and control groups are outlined in **Table 1**. Patients in both groups had similar age (i.e., group A: 74.2 ± 5.8 vs. group F: 73.9 ± 2.3; $p = 0.829$) and gender (58% males in both groups, $p = 1.000$). Patients in both groups presented with typical cardiovascular risk factors, while patients in group A had a significantly higher prevalence of diabetes (17% vs. 4.4%; $p = 0.041$) and were more frequently obese (26.3 ± 3.9 kg/m^2 vs. 24.4 ± 3.6 kg/m^2; $p = 0.019$). Four

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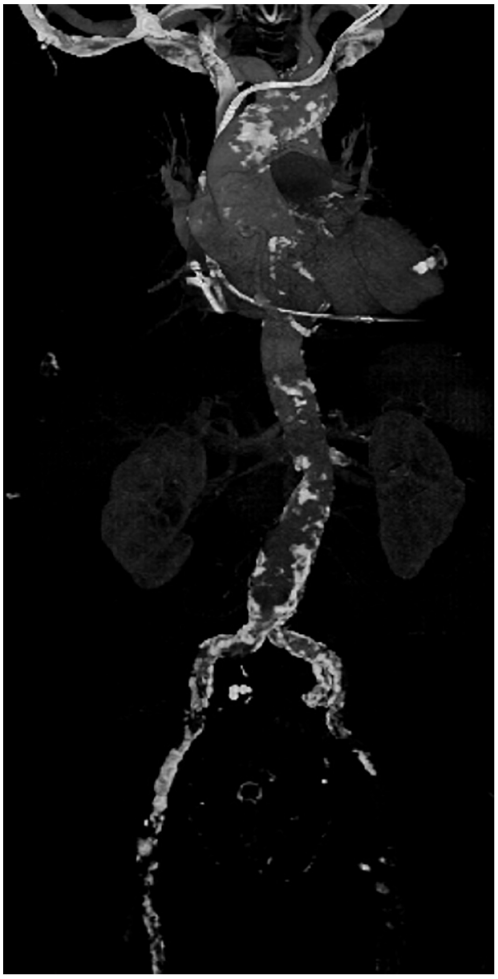

FIGURE 2
Example of a computed tomography (CT) scan of the aorta of a patient with severe arteriosclerosis in the axillary artery, aortic arch abdominal aorta and especially the femoral vessels in which minimally-invasive surgery was performed by using an antegrade arterial perfusion *via* arteria axillaris.

patients in group A suffered from infective endocarditis vs. one patient in the group F (p = 0.075). Furthermore, three patients in group A had status post stroke vs. one patient in group F (p = 0.306). Atrial fibrillation was present in 40% of the patients (group A: 54%; group F: 26%; p = 0.013), out of which 11 patients had paroxysmal or persistent atrial fibrillation. Left ventricular ejection fraction at baseline was significantly lower in group A vs. group F (49.0% ± 9.3% vs. 55.4% ± 8.1%, respectively, p = 0.001). Perioperative risk score values were significantly higher in group A vs. group F [EuroSCORE II: 3.9 ± 2.5 vs. 1.6 ± 1.5; p = 0.001; Society of Thoracic Surgeons (STS)-Score: 2.19 ± 1.49 vs. 1.31 ± 0.64; p = 0.023].

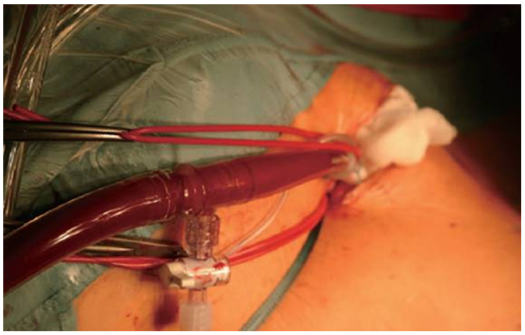

FIGURE 3
Intraoperative situs of antegrade arterial perfusion *via* axillaris artery in minimally-invasive mitral valve surgery.

Intraoperative data

MV repair was performed in 86% patients in group A vs. 96% in group F (p = 0.067). Most common concomitant procedures were left atrial ablation (group A: 10% vs. group F: 12%; p = 1.000) and LAA closure with the AtriClip® (Atricure Inc., West Chester, OH, USA) (group A: 8% vs. group F: 2%; p = 0.362) (**Table 2**). Two additional patients had closure of persistent foramen ovale in group F, while one patient in group A required simultaneous tricuspid valve repair. Cardiopulmonary bypass time (group A: 172 ± 46 min; group F: 178 ± 51 min; p = 0.627) and duration of surgery (group A: 260 ± 65 min; group F: 257 ± 69 min; p = 0.870) were similar in both groups. However, aortic cross clamp time was significantly shorter in group A as compared to group F (86 ± 20 min vs. 111 ± 29 min, p < 0.001). In group A, one patient required median sternotomy and central aortic repair due to intraoperative aortic dissection. This patient had a severe systemic atherosclerotic disease and most probably an intimal lesion was induced by the wire resulting in a type A aortic dissection. This event highlights that it is of highest importance to visualize the wire through transesophageal echocardiography and to push the wire forward without resistance. Despite this iatrogenic event the patient had an uneventful postoperative course and was discharged without neurological deficit 13 days following surgery. One patient in group A had an accidental dislocation of the axillary artery cannula during CPB and underwent emergent conversion to femoral cannulation. After this event, an additional stay suture of the cannula at the skin was placed for fixation. Consequently, no further dislocations of the cannula occurred. This particular patient had an uneventful postoperative course and was discharged home without neurological deficit 8 days following surgery.

TABLE 1 Preoperative patient characteristics: Antegrade axillary perfusion (group A) vs. retrograde femoral perfusion (group F).

Patient characteristics	Group A ($n = 50$)	Group F ($n = 50$)	p-Value
Age (years)	74.2 ± 5.8	73.9 ± 2.3	0.829
Gender—male, *n* (%)	29 (58)	29 (58)	1.000
BMI, kg/m^2	26.3 ± 3.9	24.4 ± 3.6	0.019
Arterial hypertension, *n* (%)	32 (64)	35 (70)	0.721
Diabetes, *n* (%)	7 (17)	2 (4.4)	0.041
Dyslipidemia, *n* (%)	12 (24)	12 (24)	1.000
Smoking, *n* (%)	6 (12)	2 (4)	0.144
Preoperative endocarditis, *n* (%)	4 (8)	1 (2)	0.075
Prior Stroke, n (%)	3 (6)	1 (2)	0.306
Atrial Fibrillation, *n* (%)	27 (54)	13 (26)	0.013
Baseline LVEF (%)	49.0 ± 9.3	55.4 ± 8.1	0.001
EuroSCORE II	3.99 ± 2.57	1.67 ± 1.58	0.001
STS-Score	2.19 ± 1.49	1.31 ± 0.64	0.023

BMI, Body Mass Index; EuroSCORE II, European System for Cardiac Operative Risk Evaluation; STS-Score, Society of Thoracic Surgeons-Score; LVEF, Left Ventricular Ejection Fraction.

Postoperative outcome

Duration of postoperative mechanical ventilation was significantly longer in group A vs. group F (10.1 ± 9.4 h vs. 5.9 ± 3.3 h; $p = 0.045$). However, total intensive care unit stay was similar in both groups (group A: 2.9 ± 2.6 days vs. group F: 2.1 ± 1.5 days; $p = 0.113$); **Table 3**. In-hospital stay was significantly longer in group A compared to group F (i.e., 10.0 ± 4.4 days vs. 7.1 ± 1.7 days, respectively, $p < 0.001$). In-hospital mortality was similar in both groups (group A: 1 patient; group F: 0 patients; $p = 0.289$). One patient in group A expired 5 days after surgery due to multi-organ failure. There was no in-hospital mortality in group F. In group A, a total of 6 patients required redo surgery due to bleeding vs. 4 patients in group F ($p = 0.376$). There were no perioperative stroke or vascular access-site complications in either group (**Table 3**). No further cardiovascular events occurred in the both groups.

Discussion

This study highlights implications of systemic atherosclerosis on the arterial perfusion strategy during MIS. Antegrade axillary perfusion strategy enables minimally invasive MV surgery to be performed even in high-risk patients with higher perioperative risk scores and signs of systemic atherosclerosis.

Since the turn of the 20th century, MIS MV surgery has been of increasing interest in specialized cardiac centers (3). With the help of 3D fully-endoscopic visualization and robotic assistance minimally invasive technique developed toward a well-established surgical procedure (8–10). Establishment of cardiopulmonary bypass is usually achieved *via* femoral artery cannulation. However, there has been increasing concerns about retrograde arterial perfusion in older and high-surgical risk patients (4, 11–13). In 2010, a large analysis of MIS surgery from the STS-database showed an increased risk of perioperative strokes (13). Especially in patients with beating- or fibrillating-heart techniques or use of endoaortic balloons, neurologic events occurred more often. Furthermore, Grossi et al. showed that retrograde arterial perfusion resulted in significant more neurologic events (defined as permanent deficit, transient deficit greater than 24 h or a new lesion on cerebral imaging) compared to antegrade perfusion, especially in elderly patients (5). Another recent study confirmed an increased stroke rate in the setting of retrograde perfusion in high-risk reoperative mitral valve procedures (14). However, a meta-analysis and further single-center studies showed no differences in stroke rate between retrograde vs. antegrade arterial perfusion strategy (15–19).

Murzi et al. proposed an antegrade direct cannulation of the ascending aorta in MIS which led to significant reduction of stroke and delirium compared to a propensity-matched cohort with retrograde perfusion (4). However, this approach requires a more anterior and larger incision which reduces the benefits of the minimally invasive approach. Further, a case report suggested antegrade perfusion *via* the left axillary artery for combined endoartic balloon occlusion and perfusion

TABLE 2 Intraoperative patient data.

Patient characteristics	Group A ($n = 50$)	Group F ($n = 50$)	p-Value
Mitral valve repair, *n* (%)	42 (86)	48 (96)	0.067
Concomitant procedures, *n* (%)			
Left atrial ablation, *n* (%)	5 (10)	6 (12)	1.000
LAA closure, *n* (%)	4 (8)	1 (2)	0.362
Closure of PFO, *n* (%)	0	2 (4)	0.494
Tricuspid valve repair, *n* (%)	1 (2)	0	1.000
Cardiopulmonary bypass time (min)	172 ± 46	178 ± 51	0.627
Aortic Cross-Clamp-time (min)	86 ± 20	111 ± 29	**<0.001**
Duration of surgery (min)	260 ± 65	257 ± 69	0.870

LAA, Left atrial appendage; PFO, Persistent Foramen Ovale. Significant values are highlighted in bold.

TABLE 3 Postoperative patient data.

Patient characteristics	Group A ($n = 50$)	Group F ($n = 50$)	p-Value
Access site complications	0 (0%)	0 (0%)	1.000
Perioperative stroke	0 (0%)	0 (0%)	1.000
In-hospital mortality	1 (2%)	0 (0%)	0.289
Duration ICU stay (days)	2.9 ± 2.6	2.1 ± 1.5	0.113
Duration in-hospital stay (days)	10.0 ± 4.4	7.1 ± 1.7	<0.001

ICU, Intensive Care Unit.

during robotic mitral valve surgery (20). Bonaros et al. presented a report of two patients with severe arteriosclerosis of the abdominal aorta who underwent carotid artery cannulation for antegrade perfusion during MIS (7). Furthermore, Farivar et al. reported a case series of five patients in whom antegrade arterial perfusion *via* the right axillary artery was used during MIS (21). Most recently, Puiu et al. described a large cohort of 688 patients with cannulation of axillary artery (42% with direct cannulation) and concludes that cannulation of the right axillary through a vascular prosthetic graft reduces cannulation-related complications such as iatrogenic axillary artery dissection and stroke rates (22). However, the study population described is not comparable to our mitral valve cohort, since most of them had an aortic pathology which is at more risk of iatrogenic dissection. As opposite, in our MIS mitral valve cohort we routinely use the direct cannulation of the axillary artery in Seldinger technique supported by transesophageal echocardiography guidance which is of high importance in order to visualize the wire and check for a dissection membrane. Another pitfall of the direct axillary cannulation can be the dislocation of the arterial cannula which can be prevented by a stay suture placed at the skin level in order to stabilize the arterial cannula. This technique (**Supplementary Video 1**) has been shown to be fast and reproducible and can be used in patients with higher perioperative risk scores. Therefore, this procedure provides an excellent alternative in patients with higher-risk scores who nowadays are often referred for transcatheter mitral valve treatment (e.g., MitraClip, transapical transcatheter MV replacement) (23, 24).

Furthermore, assessment of the atherosclerotic burden is crucial when planning MIS. Preoperative CT screening is performed routinely at our site to detect arteriosclerosis of the aorta or ilio-femoral vasculature in all patients >70 years and in those with signs of generalized atherosclerotic disease (e.g., evidence of carotid or peripheral artery disease) in doppler studies. Preoperative CT screening prior to MIS has also been proposed by Moodley et al. (25). Their group performs CT scans in every patient planned for MV surgery, resulting in a change of surgical approach in 21% of patients. We believe that MIS can be safely be performed in the setting of severe systemic arteriosclerosis. However, antegrade arterial perfusion, e.g., using direct cannulation of right axillary artery, seems to be advisable in such cases.

Limitations

This is a retrospective single center non-randomized analysis with all known limitations associated with such a study design and therefore drawing a final conclusion from this pilot study is limited. In addition, the patient sample is rather small. The main reason is that surgeons tend to treat patients with higher perioperative risk and severe atherosclerosis *via* median sternotomy or even refer those patients to transcatheter therapies. However, the focus of the study was to establish a standardized perfusion strategy in patients with a higher perioperative risk score undergoing MIS and to show its safety and reproducibility by analyzing perioperative outcomes. To validate this single center experience, a prospective multi-center study is necessary to confirm our current findings. Another limitation of the study is the comparison of the axillary group to a historical cohort with retrograde femoral perfusion. Nevertheless, group A includes patients with severe systemic atherosclerosis who are at higher surgical risk and therefore direct comparability is limited.

Conclusion

In summary, the burden of arteriosclerosis is an important factor to consider before MIS MV surgery. Preoperative CT screening for aortic atherosclerosis seems to be reasonable in patients age >70 years and in those with signs of generalized atherosclerotic disease. Selective use of antegrade axillary artery perfusion in patients with systemic atherosclerosis shows similar in-hospital outcomes as compared to lower risk patients undergoing retrograde femoral perfusion. Patients with higher perioperative risk and severe atherosclerosis can be safely treated *via* the minimally invasive approach with antegrade axillary perfusion.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

Author contributions

JP: conceptualization, data curation, formal analysis, methodology, investigation, and writing of original draft.

SN: data curation, formal analysis, visualization, and review and editing of draft. BK and SP: methodology, resources, and review and editing of draft. SZ: resources and review and editing of draft. YA and CD: resources, supervision, and review and editing of draft. LC and HR: methodology, resources, supervision, and review and editing of draft. EG: project administration, conceptualization, supervision, and review and editing of draft. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fcvm.2022.980074/full#supplementary-material

SUPPLEMENTARY VIDEO 1
Procedural steps of antegrade arterial perfusion *via* axillaris artery in minimally-invasive mitral valve surgery.

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Valve-sparing David procedure *via* minimally invasive access does not compromise outcome

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Objectives: Aortic valve sparing-aortic root replacement (David procedure) has not been routinely performed *via* minimally invasive access due to its complexity. We compared our results of elective David procedure *via* minimally invasive access to those *via* a full sternotomy.

Methods: Between 1993 and 2019, a total of 732 patients underwent a valve sparing root replacement (David) procedure. Out of these, 220 patients underwent elective David-I procedure (isolated) without any other concomitant procedures at our center. Patients were assigned to either group A ($n = 42$, mini-access) or group B ($n = 178$, full sternotomy).

Results: Cardiopulmonary bypass time were 188.5 ± 35.4 min in group A and 149.0 (135.5–167.5) in group B ($p < 0.001$). Aortic cross-clamp time were 126.2 ± 27.2 min in group A and 110.0 (97.0–126.0) in group B ($p < 0.001$). Post-operative echocardiography showed aortic insufficiency ≤ I° in 41 (100%) patients of group A and 155 (95%) of group B. In-hospital mortality was 2.4% ($n = 1$) in group A and 0% ($n = 0$) in group B ($p = 0.191$). Perioperative stroke occurred in 1 (2.4%) patient of group A and 2 (1.1%) patients of group B ($p = 0.483$). Reexploration for bleeding was necessary in 4 (9.5%) patients of group A and 7 (3.9%) of group B ($p = 0.232$). Follow-up was complete for 98% of all patients. The 1-, 2-, 4-, and 6-year survival rates were: 97, 97, 97, and 97%, in group A (mini-access) and 99, 96, 95, and 92% in group B (full sternotomy), respectively. The rates for freedom from valve-related re-operation at 1, 2, 4, and 6 years after initial surgery were: 97, 95, 95, and 84% in group A and 97, 95, 91, and 90% in group B, respectively.

Conclusion: Early post-operative results after David procedure *via* minimally invasive access are comparable to conventional full sternotomy. Meticulous attention to hemostasis is a critical factor during minimally access David procedures. Long-term outcome including the durability of the reimplanted aortic valve seems to be comparable, too.

KEYWORDS

aortic valve-sparing root replacement, David procedure, reimplantation procedure, minimally invasive surgery, mini access

Introduction

Minimally invasive access cardiac surgery has gained broader clinical application due to potential benefits of reduced surgical trauma and pain (1). It has been reported that patients have less pain and recover quicker from surgery (2). Especially in the field of mitral valve surgery, minimal access surgery has evolved into the standard of care in many centers.

Aortic valve-sparing root reimplantation (AVSRR) was introduced by David (3) and has become an established procedure for the treatment of combined pathologies of the ascending aorta and the aortic valve (4, 5). However, due to its complexity, David procedure is still not performed routinely *via* minimally invasive access. We started to perform AVSRR *via* mini access in 2011 and have reported our initial experience in 2015 (6). The study focusing on our initial experience comprised the first 26 patients who underwent AVSRR *via* upper hemi-sternotomy. Since then, we have gained more experience with this approach. Only few other centers have reported their experience with AVSRR through an upper hemi-sternotomy (7–9).

The present study was designed to compare patients who undergo AVSRR with mini-sternotomy with those with conventional full sternotomy.

Methods

Ethics

This is a retrospective study with follow-up. This study has been approved by our institution's Ethics Committee (Nr. 3552-2017). Thus, this study was in line with our institution's ethical policies and standards.

Study population

Our institution's database was screened for AVSRR ($n = 732$ patients) that have been performed between 1993 and 2019. All patients with concomitant procedures as well as emergent acute aortic dissection type A were excluded and only elective cases were included. Only patients who received isolated AVSRR were included. We identified 220 patients who matched these criteria. The patients were assigned to group A if access was established *via* a minimally invasive upper hemi-sternotomy ($n = 42$) or group B if access was achieved *via* a conventional full sternotomy ($n = 178$).

Surgical technique

All patients in this study underwent AVSRR with a straight tube graft (David-I). Concomitant procedures were not performed. A detailed description of our center's surgical technique of AVSRR can be found in previous publications (10), and our technique of establishing minimally invasive access in AVSRR has been published before, too (6). In brief, we perform an upper partial hemi-sternotomy into the 3rd or 4th intercostal space to establish access.

Post-operative follow up

We obtained individual consent from patients to allow for follow-up examination. Follow-up was performed as suggested by common guidelines (11). We contacted patients by telephone or met them in our center's aortic clinic. We contacted primary care physicians and cardiologists to obtain the most recent echocardiography results.

Statistical analysis

The data analysis was performed by the usage of SPSS 26 Statistics software (IBM Corp. Released 2019. IBM SPSS Statistics for Windows, Version 26.0. Armonk, NY: IBM Corp.). Normal distribution of variables was analyzed with the Shapiro Wilk test. Normally distributed continuous variables are stated as mean ± standard deviation, while continuous variables without normal distribution are stated as median + interquartile range. Continuous variables were analyzed with the Mann Whitney *U*-test, while categorical variables were compared with the Fisher's exact test. Kaplan-Meier analysis was used for evaluation of both survival and re-operation of the aortic valve, and the log-rank test was used to test for differences. A value of $p < 0.05$ was considered statistically significant.

Results

Patient demographics

The patient characteristics are shown in Table 1. All patient demographics were distributed equally between the two groups, except for BMI and Marfan syndrome. The mean age of the entire group was 47.0 (34.0–61.0) years. The majority of patients ($n = 147$, 72.4%) had significant aortic insufficiency (grade $\geq$ II°). All cases underwent elective surgery.

Intra-operative and early post-operative outcome

The intraoperative results are shown in Table 2. The cardiopulmonary bypass time was 188.5 ± 35.4 min in group

TABLE 1 Patient demographics.

	Entire group	Minimally invasive	Full sternotomy	*P*-value
Total patients (*n*)	*n* = 220	*n* = 42	*n* = 178	
Sex (male)	*n* = 162 (73.6%)	*n* = 35 (83.3%)	*n* = 127 (71.3%)	0.113
Age (years)	47.0 (34.0–61.0)	47.2 ± 14.2	47.5 (34.0–62.0)	0.990
BMI (kg/m^2)	25.4 ± 4.8	27.5 ± 3.9	24.9 ± 4.9	0.002
Hypertension	111 (50.5%)	23 (54.8%)	88 (49.4%)	0.535
Diabetes	7 (3.2%)	2 (4.8%)	5 (2.8%)	0.621
COPD	5 (2.3%)	0 (0%)	6 (3.4%)	0.586
CAD	3 (1.4%)	1 (2.4%)	2 (1.1%)	0.472
Marfan syndrome	*n* = 62 (28.2%)	*n* = 5 (11.9 %)	*n* = 57 (32.0%)	0.009
Re-Do	*n* = 6 (2.7%)	*n* = 0 (0.0%)	*n* = 6 (3.4%)	0.598
Echocardiography	*n* = 203	*n* = 39	*n* = 164	
AI 0–1	*n* = 16 (7.9%)	*n* = 4 (10.2%)	*n* = 12 (7.3%)	
AI 1	*n* = 28 (13.8%)	*n* = 5 (12.8%)	*n* = 23 (14.0%)	
AI 1–2	*n* = 12 (5.9%)	*n* = 1 (2.6%)	*n* = 11 (6.7%)	
AI ≥ 2	*n* = 147 (72.4%)	*n* = 29 (74.4%)	*n* = 118 (72.0%)	

AI, aortic insufficiency; BMI, body mass index; COPD, chronic obstructive pulmonary disease; CAD, coronary artery disease.

A and 149.0 (135.5–167.5) in group B ($p < 0.001$). Aortic cross-clamp time was 126.2 ± 27.2 min in group A and 110.0 (97.0–126.0) in group B ($p < 0.001$). The post-operative outcome is shown in Table 3. The post-operative echocardiography was available for 205 (93%) patients and showed aortic insufficiency ≤ I° in 41 (100%) patients of group A and 155 (95%) of group B. Reexploration for bleeding was necessary in 4 (9.5%) patients of group A and 7 (3.9%) of group B ($p = 0.232$). Perioperative stroke occurred in 1 (2.4%) patient of group A and 2 (1.1%) patients of group B ($p = 0.483$). In-hospital mortality was 2.4% ($n = 1$) in group A and 0% ($n = 0$) in group B ($p = 0.191$). The patient who deceased underwent mini access AVSRR and died from multi-organ failure.

Long-term outcome

Follow-up was complete for 98% of all patients. The mean follow-up time was 11.5 ± 6.7 years for the entire group. The mean follow-up times for group A was 4.2 ± 2.1 years and 13.2 ± 6.2 years for group B, respectively. The long-term survival is shown in Figure 1. The 1-, 2-, 4-, and 6-year survival rates were: 97, 97, 97, and 97%, in group A (mini-access) and 99, 96, 95, and 92% in group B (full sternotomy), respectively. The freedom from aortic valve-related reoperation is shown in Figure 2. The rates for freedom from valve-related re-operation at 1, 2, 4, and 6 years after initial surgery were: 97, 95, 95, and 84% in group A and 97, 95, 91, and 90% in group B, respectively. There was a total of 31 patients who required aortic valve-associated reoperation. The reasons for reoperation were: aortic insufficiency in 22 patients, aortic stenosis in 5 patients, and endocarditis in 4 patients.

Discussion

This study summarizes our center's experience with minimally invasive AVSRR (David-I) *via* upper hemi-sternotomy, and provides a direct comparison between mini-sternotomy and full sternotomy. The early post-operative results after David procedure *via* minimally invasive access are comparable to conventional full sternotomy. Meticulous attention to hemostasis is a critical factor during minimal access David procedures. Minimal access surgery for cosmetic and aesthetic reasons is an important factor for young patients. In elderly patients, the possibility of shorter convalescence period is the main advantage of minimal access surgery.

General and technical considerations

When AVSRR was introduced in the early 1990s, we adopted this promising technique very early in 1993 at our center. Initially, all AVSRR procedures were performed *via* full sternotomy. With growing experience and expertise, we started performing AVSRR through minimally invasive access in 2013. Only surgeons with sufficient experience in AVSRR *via* full sternotomy perform this procedure through an upper hemi-sternotomy at our center. In the present study, a total of 4 surgeons performed minimal access AVSRR, while 18 surgeons performed David procedure *via* a full sternotomy.

TABLE 2 Intraoperative data.

	Entire group	Minimally invasive	Full sternotomy	*P*-value
Total patients (*n*)	$n = 220$	$n = 42$	$n = 178$	
Aortic x-clamp time (minutes)	113.0 (100.0–128.0)	126.2 ± 27.2	110.0 (97.0–126.0)	$p < 0.001$
CPB time (minutes)	156.0 (138.0–178.0)	188.5 ± 35.4	149.0 (135.5–167.5)	$p < 0.001$
PBC (units)	0 (0–2)	0 (0–1)	0 (0–2)	0.119
GFP (units)	0 (0–3)	0 (0–0)	0 (0–4)	<0.001
Platelets (units)	0 (0–2)	0 (0–2)	0 (0–1)	0.339
Control echocardiography	$n = 205$	$n = 41$	$n = 164$	
AI 0–1	$n = 143$ (69.7%)	$n = 34$ (82.9%)	$n = 109$ (66.5%)	
AI 1	$n = 53$ (25.9%)	$n = 7$ (17.1%)	$n = 46$ (28.0)	
AI 1–2	$n = 5$ (2.4%)	$n = 0$ (0.0%)	$n = 5$ (3.1%)	
AI ≥ 2	$n = 4$ (2.0%)	$n = 0$ (0.0%)	$n = 4$ (2.4%)	

CPB, cardiopulmonary bypass; AI, aortic insufficiency.
The number of PBC, GFP and platelets given in this table refers to the intraoperatively administered products only.

TABLE 3 Post-operative outcome.

	Entire group	Minimally invasive	Full sternotomy	*P*-value
Total patients (*n*)	$n = 220$	$n = 42$	$n = 178$	
Mech. ventilation time (days)	0.5 (0.3–0.6)	0.5 (0.3–0.6)	0.4 (0.3–0.6)	0.937
Tracheostomy	4 (1.8%)	0 (0%)	4 (2.2%)	1.000
ICU stay (days)	1.0 (1.0–2.0)	1.0 (1.0–2.3)	1.0 (1.0–2.0)	0.364
In-hospital mortality	$n = 1$ (0.5%)	$n = 1$ (2.4%)	$n = 0$ (0%)	0.191
PBC (units)	2 (0–4)	2 (0–4)	2 (0–4)	0.961
FFP (units)	3 (0–4)	0 (0–2)	3 (2–5)	<0.001
Platelets (units)	0 (0–2)	1 (0–2)	0 (0–2)	0.149
Reexploration for bleeding	$n = 11$ (5.0%)	$n = 4$ (9.5%)	$n = 7$ (3.9%)	0.232
Stroke	$n = 3$ (1.4%)	$n = 1$ (2.4%)	$n = 2$ (1.1%)	0.483
Dialysis	$n = 1$ (0.5%)	$n = 1$ (2.4%)	$n = 0$ (0%)	0.196

ICU, intensive care unit; PBC, packed blood cells; FFP, fresh frozen plasma.
The number of PBC, GFP and platelets given in this table refers to the total units administered during the entire hospital stay.

With regards to selection criteria, we consider every patient eligible for AVSRR if it is an isolated David procedure if the surgeon has sufficient expertise. Concomitant hemiarch replacement can also be performed safe through an upper hemi-sternotomy. However, if there are any other concomitant cardiac surgical procedures (for instance coronary artery bypass grafting, total aortic arch replacement, or mitral valve surgery), a full sternotomy is performed.

When evaluating patients for mini-access AVSRR, we pay careful attention to the anatomic location of the aortic root on computed tomography scan. The scan determines whether the 3rd or 4th intercostal space is used for access.

Minimally invasive access AVSRR requires careful performance of the anastomoses, and meticulous hemostasis. It is key to achieve perfect hemostasis, because bleeding from the aortic root is hard to control in minimally invasive access cardiac surgery. Significant bleeding may even require another pump run.

Early outcome

In the present study, both the cardiopulmonary bypass and the aortic cross clamp times were longer in the minimally invasive access group than in the full sternotomy group. However, this did not lead to an increased incidence of myocardial ischemia-related complications. We did not observe an increased rate for post-operative low cardiac output syndrome in the mini access group.

The usage of fresh frozen plasma during the operation and during the entire hospital course was significantly higher in the full sternotomy group. This can be explained by the

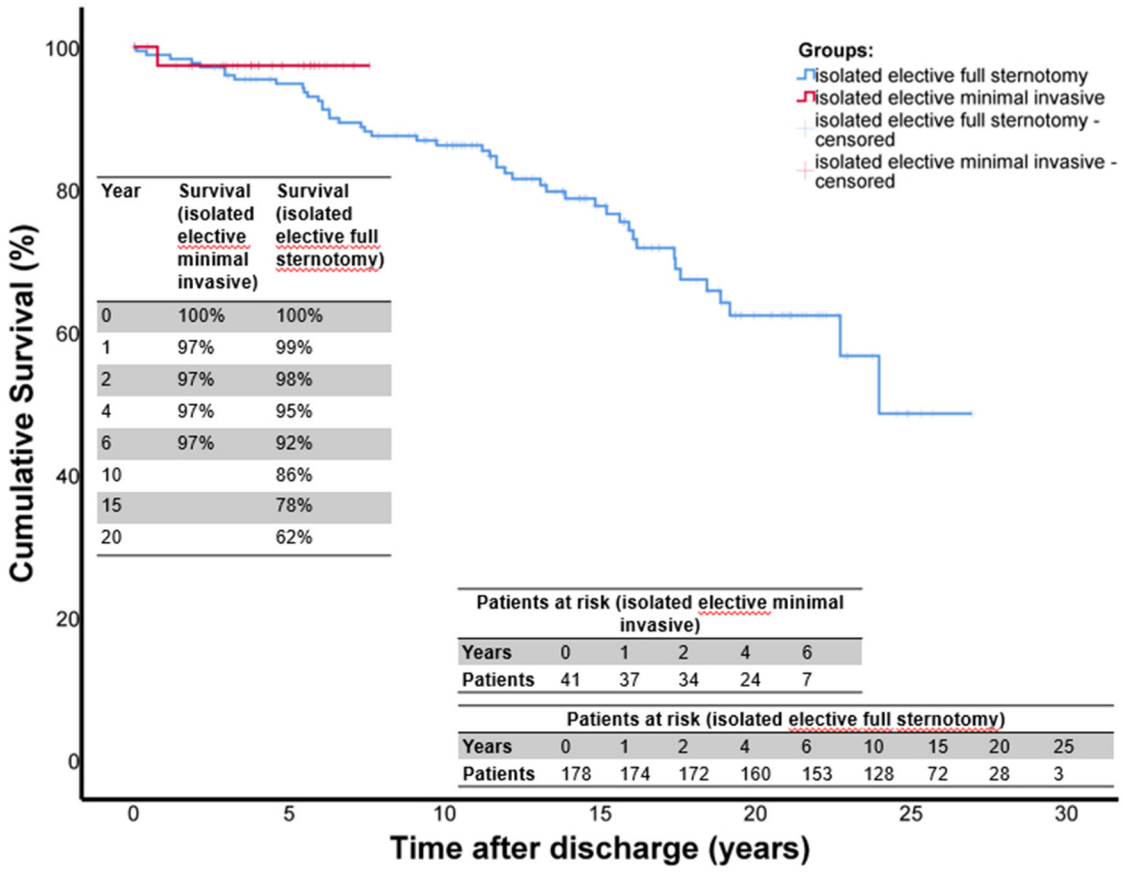

FIGURE 1
Survival after isolated elective AVSRR. This figure shows the Kaplan Meier survival curves for patients who underwent isolated, elective David-I procedure. The red curve shows the mini access patients (group A) and the blue curve shows the full sternotomy patients (group B). Time origin on x-axis denotes day of surgery.

more invasive access and trauma in the full sternotomy course. Further, this finding also underlines that meticulous hemostasis is very important during minimal access AVSRR.

There was only one perioperative death in the entire study, resulting in an overall in-hospital mortality of 0.5%. In comparison, the operative mortality in Tirone David's group was 1% (4). The patient who deceased in our study died because of multiorgan failure. This patient underwent mini access AVSRR, and since the mini access group is relatively small the in-hospital mortality is 2.4%. Although there was no early death in the full sternotomy group, we do not think that mini access was linked to the death of this patient. Given the low in-hospital mortality of 0.5% of the entire cohort, we think that this demonstrates that full aortic root replacement using a valve-sparing technique can be done extremely safe. Clearly, careful patient selection is important.

The perioperative incidence for permanent neurological deficit was 1.5% in the entire cohort. This is an encouraging low number, too. However, the rate for reexploration for bleeding was slightly higher in group A (mini access) than in group B (full sternotomy). Although minimally invasive cardiac surgery is known to reduce trauma and facilitate post-operative recovery (2), one has to assume that hemostasis in mini access aortic root surgery is more complicated. We conclude that more attention should be directed toward meticulous hemostasis in order to prevent reexploration.

The post-operative echocardiographic data showed comparable results in the two groups. For instance, echo showed aortic insufficiency $\leq$ I° in 41 (100%) patients of group A and 155 (95%) of group B. Therefore, we conclude that mini access does not compromise the quality of the preserved and reimplanted aortic valve.

Long-term outcome

We started AVSRR in 1993 at our center and by now, we have done more than 700 AVSRR operations. Using a

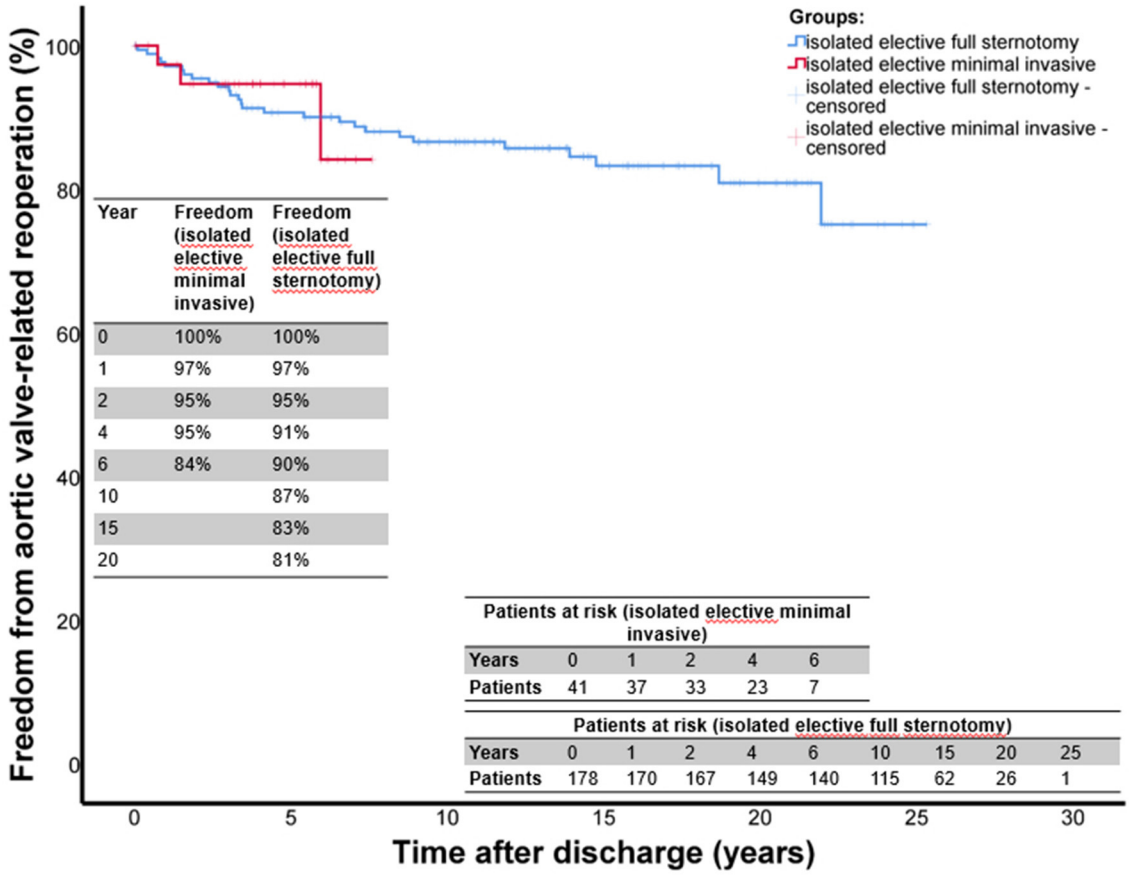

FIGURE 2
Freedom from aortic valve-related reoperation after isolated elective AVSRR. This figure shows the Kaplan Meier curves for freedom from aortic valve-related reoperation after isolated, elective David-I procedure. The red curve shows the mini access patients (group A) and the blue curve shows the full sternotomy patients (group B). Time origin on x-axis denotes day of surgery.

minimally invasive approach *via* upper partial sternotomy has been introduced later. First, mini access was applied to relatively simple operations such as aortic valve replacement, and later—with growing experience—also to more complicated procedures. We applied min access to AVSRR in 2013, almost 20 years after the first David procedure at our hospital. This explains the smaller sample size and the shorter follow up time of the mini access group when compared to the conventional group. In turn, it is difficult to compare and comment on the long-term durability and performance of the reimplanted aortic valve in group A. At least for the mid-term outcome, we observed no major difference in aortic valve-related reoperations between the two groups. The same seems to be true for mid-term survival. Future studies will have to clarify whether survival and aortic valve durability after mini access AVSRR are adequate in the long term.

Although we expect comparable long-term outcome after minimally invasive access AVSRR, we want to emphasize that only experienced surgeons should perform David procedure *via* mini access. Despite the encouraging outcome in the present study, David procedure remains a complex operation. Surgeons go through a learning phase until having sufficient results with this technique (12). Therefore, we think that a step-by-step approach is recommended to establish minimally invasive David procedure. Surgeons should have sufficient expertise and experience with AVSRR *via* full sternotomy before starting mini access. Then, surgeons should start with simple operations first through an upper hemi-sternotomy, such as conventional aortic valve replacement. With growing experience with this approach, more complicated procedures can be performed *via* mini access.

Limitations

This is a retrospective study which carries all potential risks and disadvantages of this study type. The sample size of the mini access group is relatively small, and follow up time shorter than in the full sternotomy group. There is potential selection bias,

as more experienced surgeons may have performed minimally invasive access cardiac surgery.

Conclusions

The present study provides a direct comparison of AVSRR with a mini-sternotomy and conventional full sternotomy. The early post-operative results after David procedure *via* mini access are comparable to full sternotomy. Meticulous attention to hemostasis is a critical factor during minimally invasive access David procedures. Long-term outcome including the durability of the reimplanted aortic valve seems to be comparable, too, but longer follow up times are needed.

Data availability statement

The datasets presented in this article are not readily available because the data underlying this article cannot be shared publicly because due to privacy issues. The International Committee of Medical Journal Editors (ICMJE) emphasizes that patients and study participants have a right to privacy that should not be infringed without informed consent. Study participants should know exactly how their data will be used and shared. Although our patients gave informed consent to participate in this study, we did not ask them to give consent to share their anonymized data publicly. For this reason and to be in line with the recommendations of the ICMJE, we cannot make the data publicly available. Reasonable requests to the corresponding author will be evaluated. Requests to access the datasets should be directed to shrestha.malakh.lal@mh-hannover.de.

Ethics statement

The studies involving human participants were reviewed and approved by Hannover Medical School Ethics Committee. The patients/participants provided their written informed consent to participate in this study.

Author contributions

All authors were involved in the conceptualization, data collection, data analysis, and writing the article.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Lessons learned from 10 years of experience with minimally invasive cardiac surgery

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Since its inception more than a quarter of a century ago, minimally invasive cardiac surgery has attracted the increasing interest of cardiac surgeons worldwide. The need to surgically treat patients with smaller and better-tolerated incisions coupled with high-quality clinical outcomes, particularly in structural heart disease, has become imperative to keep pace with the evolution of transcatheter valve implantation. We have learned numerous lessons from our longstanding experience in this field of surgical care, especially in terms of endoscopic access *via* mini-thoracotomy. To improve the safety and efficacy of this minimally invasive endoscopic access, this study summarizes and highlights the lessons we have learned, acting as a template for newly established cardiac surgeons in minimally invasive techniques.

KEYWORDS

minimally invasive surgery, cardiac surgery, lessons learned, aortic valve, mitral valve

Introduction

The term "minimally invasive cardiac surgery (MICS)" covers a vast field of procedures, including valve surgeries, coronary artery bypass graft surgery (CABG), and intracardiac tumor resections, and has shown success in terms of safety and efficacy compared to conventional sternotomy (CS) (1). MICS techniques allow heart operations to be performed and enable access to the relevant anatomical structures through substantially smaller incisions. These patient-friendly techniques in turn help to avoid the excessive dissection of surrounding tissues and even circumvent the need for a cardiopulmonary bypass (CPB), thereby leading to a faster post-operative recovery period and a cosmetically superior result for the patient (2). Although MICS approaches provide indisputable benefits to the patient, most studies report a correspondingly longer time for extracorporeal circulation and cardiac arrest with the minimally invasive approach. However, MICS benefits both from the utilization of video-thoracoscopic assistance and from advancements in CPB techniques to offer advantages such as a reduction in cross-clamp times, CPB times, and ventilator support, as well as shorter intensive care and total hospital time (3, 4).

Minimally invasive cardiac surgery approaches mainly include the upper and the lower mini-sternotomy, parasternal approach as well as the right and the left mini-thoracotomy to perform isolated or multiple valve surgery, CABG, intracardiac tumor resections, or atrium septum defect closure, considering the peculiarities of each technique for each procedure. In the last few years, the use of endoscopic minimally invasive access *via* mini-thoracotomy to reach different cardiac structures has gained popularity among surgeons who perform minimally invasive cardiac surgery. The steep learning curve and technical difficulties of the different procedural steps such as CPB cannulation, myocardial protection, and deairing maneuvers discourage many surgeons from including these minimally invasive procedures in their routine surgical practice (5).

This study summarizes the lessons learned from our decade-long experiences using different approaches to MICS, with an emphasis on minimally invasive endoscopic mini-thoracotomy to encourage cardiac surgeons to adopt this technique for safety and feasibility.

Lesson 1: Patient selection

In our opinion, the final decision on the operative strategy for each patient requires that cardiac surgery be performed on an individual-to-individual basis during a pre-operative medical staff meeting by taking into consideration the pre-operative demographic data of the patient such as age, comorbidities, vascular status, and EuroSCORE II (European System for Cardiac Operative Risk Evaluation II). The choice of the surgical technique is the net result of the application of an internal policy recommendation, which is exactly tailored to meet the requirements of an individual patient. An increased EuroSCORE and the age of the patient alone are not contraindications for endoscopic MICS. Elderly patients benefit even from the slightest advantages of endoscopic MICS by decreasing surgical trauma and perioperative pain, blood transfusions, hospital and intensive care unit (ICU) length of stay, ventilation time, wound infections, cost of hospitalization, and rehabilitation when compared to the CS. Moreover, for the young patient group, these techniques improve the cosmetic, quality of life, and patient satisfaction with an earlier return to normal activities (3, 4, 6). Even patients with difficult anatomical conditions, such as pectus excavatum or dextrocardia by situs inversus (DSI), are suitable for an endoscopic MICS when performed at experienced MICS centers. We published the first report of an endoscopic aortic valve replacement (AVR) through left anterior mini-thoracotomy in a patient with DSI. The recognition of anatomical abnormalities through a careful evaluation of the pre-operative diagnostics and the rearrangement of the operation theater equipment in a mirror-image fashion by adapting the surgical technique to the reversed anatomy are fundamental to the success of this concept (7).

Several structural pathologies of the heart including extensive endocarditis or severe calcification of the mitral valve (MV) annulus or severe calcification of the abdominal and/or iliac aorta are major limitations of this technique (Table 1). Therefore, computer tomography angiography (CTA) of the aorta and the arterial vascular system remains a very important pre-operative diagnostic tool for deciding a patient's eligibility for an endoscopic MICS procedure.

Lesson 2: Surgical equipment

Minimally invasive cardiac surgery has been reported to be technically more challenging than conventional surgery because surgeons are confronted with a restricted view of the operating field with a concurrent, relatively long distance between the skin incision and the anatomical structures of the heart. These difficulties have been reported to be responsible for longer operating times and longer CPB and cross-clamp times observed with this procedure (8). In our view, these challenges in endoscopic MICS can be resolved and facilitated by using various devices such as a three-dimensional (3D) camera (Aesculap Einstein Vision, Tuttlingen, Germany), long surgical instruments, and an automatic suture fastener system (Cor-Knot®, LSI Solutions, Rochester, NY, USA) (Figure 1).

a) The use of a 3D camera is preferred:
- to enable the surgery to be undertaken in an endoscopic manner using only a soft tissue retractor without rib

TABLE 1 Contraindications for endoscopic minimally invasive cardiac surgery.

Extensive endocarditis
Several calcifications of the aortic or mitral valve annulus
Several calcifications of the thoracal and/or abdominal aorta
Hostile aortic root
Severe peripheral artery disease
Severe adhesions of the lung
Extreme left deviated heart axis

Abbreviations: AV, Aortic valve; AVR, Aortic valve replacement; CPB, Cardiopulmonary bypass; CS, Conventional sternotomy; CTA, Computer tomography angiography; DSI, Dextrocardia with situs inversus; MICS, Minimally invasive cardiac surgery; MR, Mitral regurgitation; MV, Mitral valve; RAMT, right anterior mini-thoracotomy; TV, Tricuspid valve; VCD, Vascular closure device.

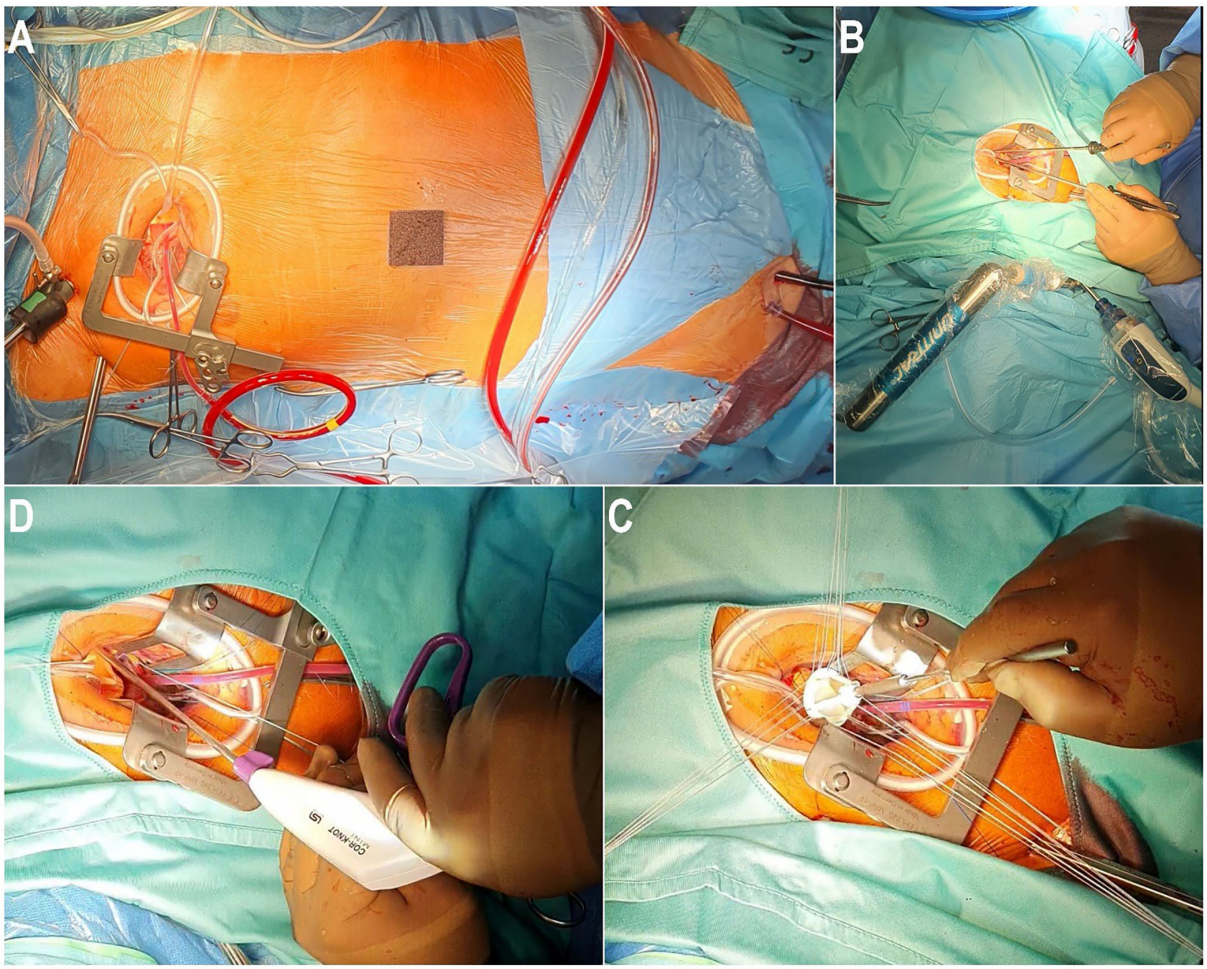

FIGURE 1
Operative setup of an endoscopic aortic valve replacement through right anterior mini-thoracotomy. **(A)** Right anterior mini-thoracotomy with percutaneous cannulation of the cardiopulmonary bypass. **(B)** Endoscopic placement of the aortic annular suture using long shaft instruments. **(C)** Implantation of the aortic valve prosthesis. **(D)** Introduction of Cor-Knot® to fix the aortic valve prosthesis.

resection and without using a rib retractor to reduce post-operative pain,
- to securely place the Chitwood clamp (Scanlan International, Inc., St Paul, MN, USA) on the aorta under full camera visualization to avoid any possible injury to the pulmonary artery or the left atrial appendage, and
- to enable the surgeon to see all parts of the operating field and to properly resect the leaflets, to radically decalcify the valve annulus, and to precisely place the annulus sutures, especially in cases of left-sided deviated heart or the bicuspid valve with limited exposure of the aortic valve (AV).

b) Likewise, the use of long surgical instruments enables access to all structures of the aorta and the heart.

c) The fixation of the valve prosthesis in the annulus can also be more easily, rapidly, and securely performed by using automated knot technology.

All these instruments simplify and facilitate the procedure, thereby reducing the operating time without compromising the safety and the efficacity of the technique (3).

Lesson 3: Learning curve of the surgeon

As regards the learning curve, we believe that beginner surgeons must have at least experience with performing conventional surgery involving a minimum of 100 cases in each procedure [AV, MV, and tricuspid valve (TV) surgery]. Simultaneously, they must undergo or should have undergone dry training with an endoscope, which is mandatory to achieve an imagination in endoscopic surgery. The first cases must be carefully selected for endoscopic MICS by considering the body mass index (BMI) under 30, favorable anatomical

conditions of the heart and the chest, and a non-complex underlying pathology.

The assistance of an experienced surgeon in endoscopic MICS is a fundamental requirement at this learning stage. Another aspect that contributes to facilitating the surgical procedure is clear and effective communication between the surgeon, the anesthetist, the perfusionist, and the scrub nurse. Considerable experience in performing MICS is required for all the above mentioned members (3).

From our experience, we can easily speculate that new surgeons feel technically safe from 50 cases onward and the operative time decreases by increasing the number of operated cases.

Lesson 4: Cannulation and clamping

Arterial and venous femoral cannulation for the CPB is the standard procedure used to perform an endoscopic MICS through mini-thoracotomy. Preoperative CTA of the aorta is crucial to determining whether the MICS procedure is suitable for the patient (4). Severe calcification of the femoral, abdominal, and/or thoracic aorta, and/or severe kinking in the aorta constitute contraindications for arterial femoral cannulation for CPB (Table 2). Indeed, arterial femoral cannulation for CPB in the right axillary artery represents an excellent alternative to avoid low cerebral perfusion and retrograde perfusion in cases of calcification of the abdominal, iliac, or thoracic aorta. Previous surgery of the groin, the presence of femoral or abdominal/thoracal aortic stent/prosthesis, and fungal groin infection represent further contraindications for femoral cannulation for CPB.

At the beginning of a MICS procedure, surgical access in the right groin is made through a 2- to 3-cm skin incision below the inguinal ligament, followed by insertion of the femoral cannula (Bio-Medicus multistage femoral venous cannula, Medtronic, Minneapolis, MN, USA) to the level of the superior vena cava (SVC) and the arterial cannula (Bio-Medicus arterial cannula, Medtronic, Minneapolis, MN, USA) to the level of the right external iliac artery. While in the conventional open surgical approach, the common femoral artery is directly sutured under direct vision after decannulation, the percutaneous innovative collagen-based MANTA™ Vascular Closure Device (VCD) (Essential Medical, Inc., Malvern, PA, USA) is used in MICS. It serves as an elegant, safe, and reproducible closure device to manage this small bore access by immediate sealing (9). Otherwise, suture-based vascular closure devices, such as Perclose ProGlide and ProStar XL (Abbott Vascular, Santa Clara, CA, USA), are readily used for the closure of large bore access. Notably, we recommend new surgeons in endoscopic MICS initiate the learning curve with surgical access and closure for CPB cannulation. After 50 cases, ultrasound-guided percutaneous femoral cannulation for CPB can be used in combination with the use of MANTA™ VCD to avoid surgical complications of the groin. Our experience with MANTA™ system demonstrates this tool to be an effective, fast, and safe device, which also has a positive effect on the operating time compared to the surgical access for CPB in endoscopic MICS (9, 10).

TABLE 2 Contraindications for arterial femoral cannulation for cardiopulmonary bypass.

Severe calcification of the femoral or iliac artery
Severe calcification of the abdominal and/or thoracal aorta
Severe kinking in the aorta
Femoral or abdominal/thoracal aortic stent/prosthesis
Groin infection

As regards clamping of the aorta, we routinely use the Chitwood clamp. Alternatively, endoaortic balloon (EAB) occlusion with the endoaortic balloon clamp (Johnson & Johnson Corp, New Brunswick, NJ, USA), which is introduced from the femoral artery into the ascending aorta right above the sinotubular junction, can be used (11). Crystalloid cardioplegia (Custodiol; Koehler Chemi, Alsbach-Haenlien, Germany) is administered in an antegrade fashion through a long cardioplegia catheter (Medtronic DLP 9F, Ref 10012) into the ascending aorta and then directly into the coronary ostia in cases of aortic regurgitation.

Lesson 5: Aortic valve

The partial upper sternotomy (PUS) procedure remains the best surgical access in MICS for AVR, which can be performed by a wide range of surgeons (4). However, endoscopic minimally invasive AV surgery *via* right anterior mini-thoracotomy (RAMT) is a safe and feasible technique without compromising on the surgical quality, the post-operative outcomes, or the patient safety when performed by a team very well-experienced in performing MICS (3, 4). Computed tomography (CT) criteria for eligibility for AVR *via* RAMT with regard to the assessment of the ascending aorta and AV position and depth are previously described in the literature (12). Severe calcified or small aortic annulus (<19 mm), hostile aortic root or ascending aorta, extensive endocarditis, severe adhesions of the lung, and/or extreme left deviated heart axis remain the common contraindications for AVR *via* RAMT. In our opinion, standard lung ventilation with a 1-lumen tube is sufficient for performing this technique (3).

The skin incision is limited to 3–5 cm longitudinally and 3 cm to the right of the midline of the sternum at the level of the third intercostal space (ICS). The chest wall access is a keyhole through the third ICS using a soft tissue retractor (ValveGate™ Soft Tissue Protector, Geister, Germany) for optimal exposure

without resection or dislocation of the rip and for preserving the right internal thoracic artery and vein intact. The 3D camera port access and Chitwood clamp are usually placed medially and laterally, respectively, *via* the second ICS. The pericardium is opened 5 cm above the phrenic nerve between the innominate vein cranial and the inferior vena cava (IVC) caudal. The use of two stay sutures on the right side of the pericardium superiorly and inferiorly to the right superior pulmonary vein helps to reduce the work distance. Multiple 4–0 Prolene stay sutures in the aortic wall and the aortic valve commissures help in the exposure of the valve. In some cases, the AV annulus sits below the third ICS, requiring surgeons to face the challenge of working through a tunnel. Therefore, long-shaft instruments belong to the standard surgical setup for MICS. For a newly established surgeon in MICS, patient selection is an important step, and they should carefully consider the pre-operative anatomical CTA findings of the concerned patient (3).

The use of the 3D camera in AV surgery allows the surgeon to resect the leaflets properly, radically decalcify the valve annulus, and place the annulus sutures precisely, especially in the right coronary sinus. In cases of bicuspid AV, the role of the 3D camera is very important for localizing the left and right coronary sinus for a geometric ideal placement of the AV prosthesis beginning from the knots at the right coronary sinus (3).

Lesson 6: Mitral valve

For the MV, endoscopic MICS has been performed extensively over the last three decades using various techniques such as the parasternal and transsternal approaches and partial upper and lower sternotomy, allowing for direct visualization and manipulation of the MV (13). Video-assisted RAMT for MV surgery remains the most commonly used MICS as it has several advantages compared to CS (14). The challenge of using this technique is to provide an equal or superior surgical outcome to conventional procedures, ensuring intraoperative quality control by documenting a successful elimination of significant mitral regurgitation (MR).

Through a 3–5 cm skin incision or a peri-areolar skin incision with a nipple-cut approach over the fourth ICS and with the optimization with assistance from a 3D camera, the exposure of the MV is obtained through dissection of the interatrial groove, left atriotomy, and using a left atrial retractor (Valve Gate™ Holders Set Mitral, Geister, Germany). Considering their excellent long-term durability, simple, and efficacious MV repair is preferred over MV replacement in the treatment of degenerative MR in terms of superior early and late survival, improved reverse ventricular remodeling and ejection fraction (EF) recovery, and a better quality of life (15, 16). MICS for MV repair provides excellent exposure of the MV and the sub-valvular apparatus, including the base of papillary muscles, allowing an optimal placement of sub-annular sutures for ring annuloplasty, leaflet resection, or augmentation, as well as uncomplicated implantation of the loops and polytetrafluorethylene neo-chords on the corresponding papillary muscle and MV leaflet when the loop technique is required (17).

The complexity of MV reconstruction makes the MICS procedure more challenging for surgeons who require a longstanding experience in this technique. Thus, we believe that surgeons must first become thoroughly proficient in performing the MICS for MV replacement and standard open MV repair before practicing these techniques in an almost closed chest.

Moreover, this technique allows the performance of concomitant procedures when cryomaze ablation, closure of a patent foramen oval, and/or left atrial appendage closure using AtriClip™ (AtriCure, Inc., Mason, OH, USA) are required. In this regard, concomitant trans-mitral septal myectomy and MV surgery *via* RAMT were enrolled in our experience in endoscopic MICS performing 14 cases safely with excellent surgical outcomes (17). Moreover, the endoscopic MICS approach for MV reoperation in selected high-risk patients seems to be safe and feasible (18).

Lesson 7: Tricuspid valve

Minimally invasive cardiac surgery for the tricuspid valve (TV) is mostly performed as a concomitant procedure to MV surgery with increased incidence due to various reasons, which include an increase in the implantation of intracardiac devices and the prevalence of atrial fibrillation (19). Venous cannulation in cases of MICS for TV varies between cardiac centers considering the expertise of the team, the cost-effectiveness of the procedure, and the reproducibility of the procedure (20). Classically, percutaneous bicaval venous cannulation through the external jugular and femoral veins and arterial cannulation through the common femoral artery is the most performed cannulation technique for CPB in MICS for TV at our department. To switch to total bypass, we use Bulldog vascular clamps for the superior vena cava and the inferior vena cava due to their effectiveness and rapid use without resorting to additional dangerous manipulations. The TV is exposured through the right atrium using an atrial retractor (ValveGate™ Holders Set Tricuspidal, Geister, Germany). Thereafter, complex surgical techniques for the repair and replacement of the TV can be safely performed in a beating heart fashion with the same quality as those of the CS approach (21, 22). Beating heart MICS techniques decrease or eliminate potential myocardial injury from ischemia time and the spare additional maneuvers of aortic cross-clamping and clamp release.

Conclusion

Our experience with endoscopic MICS suggests that this concept can be safely, effectively, and reproducibly performed by a wide range of surgeons. This study is intended to serve as a template for newly established cardiac surgeons in minimally invasive techniques in the hope of accelerating the learning curve while improving patient outcomes.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

AE-S and FB contributed to conception and design of the study. SS wrote the first draft of the manuscript. AE-S wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

Conflict of interest

FB discloses speakers' honoraria and/or consulting fees from Edwards Lifesciences, LIS, and Abbott.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Postoperative results of minimally invasive direct coronary artery bypass procedure in 234 patients

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Introduction: Minimally invasive approach in cardiac surgery has gained popularity. In order to reduce surgical trauma in coronary surgery minimally invasive direct coronary artery bypass (MIDCAB) has already been established. This technique has been introduced for revascularisation of isolated left anterior descending (LAD). It can also be performed for hybrid revascularisation procedure in multi-vessel disease.

Methods: From 2017 to 2021, 234 patients received MIDCAB operation in our heartcenter 73% were male. Most of the patients had two or three vessel disease (74%). The average age of the patients was 66 ± 12 years mean. The left internal mammary artery (LIMA) was anastomosed to the LAD through left minithoracotomy approach. Multi-vessel MIDCAB (MV-MIDCAB) including two anastomoses (T-graft to LIMA with additional saphenous vein graft) was done in 15% (n = 35).

Results: The average operation time was 2.3 ± 0.8 h mean. The 30-day mortality was 1.7% (n = 4). The average amount of packed red blood cells (pRBC) that was given intra- and postoperatively was 0.4 ± 0.8 units mean. The mean intensive care unit stay (ICU) was 1 ± 1.2 days. Three patients (1.3%) had wound infection postoperatively. The rate of neurologic complications was 0.4% (n = 1). Two patients (0.9%) had myocardial infarction and received coronary re-angiography perioperatively including stent implantation of the right coronary artery.

Discussion: The MIDCAB procedure is a safe and less traumatic procedure for selected patients with proximal LAD lesions. It is also an option for hybrid procedure in multi-vessel disease. The ICU stay and application of pRBC's are low. Our MIDCAB results show a good postoperative clinical outcome. However, follow-up data are necessary to evaluate long-term outcome.

KEYWORDS

minimally invasive, off-pump surgery, minithoracotomy, hybrid procedure, left anterior descending

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Introduction

Minimally invasive cardiac surgery for the treatment of valve disease is well-established. Coronary artery bypass grafting (CABG) *via* minimally invasive approach is an outstanding evolution in cardiac surgery. Since the first beating heart anastomosis was described by Kollesov in 1967 (1) the Off-pump bypass surgery technique has been developed continuously during the past decades. Minimally invasive direct coronary artery bypass (MIDCAB) grafting was presented in the 1990s by Calafiore and Subramanian (2, 3). Today it is an important part of the cardiac surgery armamentarium in centers of excellence. MIDCAB procedure is a revascularization strategy for the treatment of left anterior descending (LAD) disease. It can also be applied as a hybrid coronary revascularization (HCR) in the setting of incomplete surgical revascularization for high-risk patients. These patients usually undergo postoperative interventional percutaneous coronary intervention (PCI). In selected patients multi-vessel MIDCAB is feasible to treat lesions of LAD, diagonal branch or circumflex artery. Less surgical trauma, reduced operative bleeding, and fast recovery are associated with MIDCAB approach (4–6). Despite the advantages of MIDCAB procedure this technique has not been widespread in the routine cardiac surgery field. It might be related to the fact that MIDCAB remains technically challenging due to limited access to the surgical situs and limitation of exposure of the heart (5). Another reason could be that CABG and PCI are indexed for class IA category for treatment of isolated proximal LAD lesions in the guidelines on myocardial revascularization (7). Therefore the desicions of heartteams play an important role to enclose the suitable patients for this minimally invasive procedure.

Patients and methods

Study population

From 2017 to 2021, 234 patients underwent MIDCAB procedure in Heartcenter Siegburg and University Hospital Bonn. 27% were female. The majority of patients had two or three vessel disease (74%). Patients' mean age was 66 ± 12 years. The left internal mammary artery (LIMA) was anastomosed to the LAD *via* left minithoracotomy approach in all patients. MV-MIDCAB with two anastomoses (additional saphenous vein graft as T-graft to LIMA) was performed in 35 patients (15%). The patients' preoperative characteristics are summarized in **Table 1**.

This retrospective study was approved by the local ethics committee (#446/21).

Patient selection criteria

Suitable patients for MIDCAB were discussed in a heartteam for the surgical/hybrid procedure. Inclusion criteria were significant stenosis or occlusion of the proximal or medial LAD for single vessel revascularization. The diagonal branch or ramus intermedius were targets for multi-vessel revascularization. For HCR the right coronary artery and/or circumflex artery were treated with PCI postoperatively. Exclusion criteria were former chest radiation or left thoracotomy (for lung or breast surgery), stenosis of the left subclavian artery, emergency operation, and/or hemodynamically instable patients, or redo CABG.

Surgical technique

Patients were placed in a supine position, with 30° elevation of the left thorax. Intubation was established

TABLE 1 Patients' characteristics.

Number, *n*	234
Age (mean, years)	66 ± 12
Male	173 (73%)
NYHA class (mean)	3 ± 0.5
CCS class	3 ± 0.7
One-vessel CAD	62 (26%)
Two-vessel CAD	70 (30%)
Three-vessel CAD	102 (44%)
Ejection fraction (mean, %)	51 ± 10
Comorbidities	
Diabetes mellitus type 1	3 (1%)
Diabetes mellitus type 2	45 (19%)
COPD stage 1 (mild)	4 (1.7%)
COPD stage 2 (moderate)	20 (8.6%)
Renal failure stage 2	22 (9.4%)
Renal failure stage 3	23 (10%)
Renal failure stage 4	9 (3.8%)
Renal failure stage 5	1 (0.4%)
Myocardial infarction	70 (30%)
Arterial hypertension (%)	159 (68%)
EUROScore II (mean)	3 ± 3.6
Hemoglobin (mean, gr/dl)	12.6 ± 2
PAD	25 (11%)
PCI, stent	77 (33%)

NYHA, New York heart association; CCS, Canadian cardiovascular society; CAD, coronary artery disease; COPD, chronic obstructive lung disease; COPD stage 1: FEV1 > 80%; COPD stage 2: FEV1 50–80%; PAD, peripheral arterial disease; PCI, percutaneous coronary intervention; diabetes mellitus type 1 (insulin dependent), type 2 (non-insulin dependent); renal failure stadium 2: GFR 60–89 ml/min/1.73 m^2, renal failure stadium 3: GFR 30–59 ml/min/1.73 m^2, renal failure stadium 4: GFR 15–29 ml/min/1.73 m^2, renal failure stadium 5: GFR < 15 ml/min/1.73 m^2.

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with a double-way endotracheal tube. A 5–8 cm long left submammary or supramammary skin incision was done, and the left pleural space was entered through the 4th or 5th intercostal space. The left lung was deflated. With the help of a MICS retractor for LIMA (lifting retractor, Geister, Tuttlingen, Germany) a pedicled LIMA graft was harvested (**Figure 1**). Systemic heparinization was initiated, the pericardium was opened, and the LAD was identified. The distal anastomosis was performed Off-pump with the help of a vacuum tissue stabilizer (Octopus Evolution, Medtronic, Minneapolis, USA) and an intracoronary shunt (Medtronic, Minneapolis, USA). A traction suture with tourniquet was placed with 4/0 polypropylene to the proximal part of the LAD. Air/saline insufflation was used to achieve a bloodless operation field. Bypass flow was measured routinely intraoperatively. In MV-MIDCAB a small segment of saphenous vein was harvested from the lower leg. The venous graft was anastomosed to the target vessel in a same manner. Finally the proximal anastomosis (T-Graft to LIMA) was performed. If necessary a heart positioner was applied for better exposition (Starfish Evo, Medtronic, Minneapolis, USA). Protamin was administered 1:1, a thorax drain was placed into the left pleura and thoracotomy was closed.

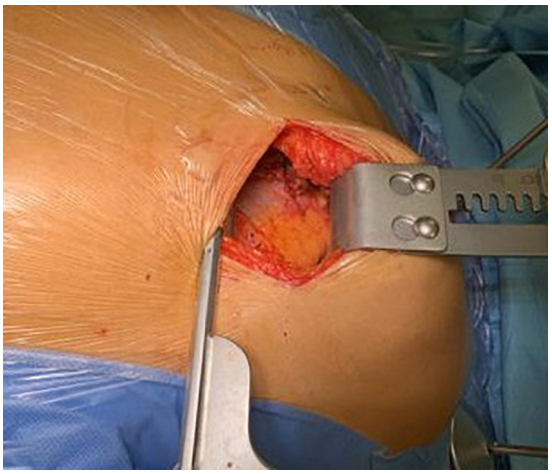

FIGURE 1
Left thoracotomy for LIMA harvesting using a lifting retractor.

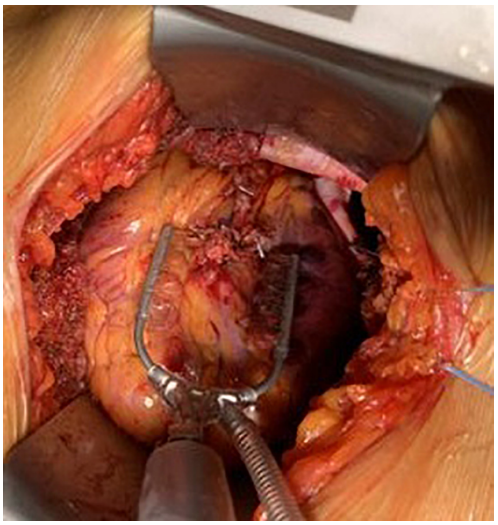

FIGURE 2
Minimally invasive direct coronary artery bypass, LIMA, to LAD anastomosis.

Statistical analysis

Statistical analyses were calculated with the biometrically analysis of sampling software (BIAS 11.06, Frankfurt, Germany). Categorical data were presented as percentages and continuous data were illustrated as mean value ± standard deviation.

Results

The majority of patients (85%) received single bypass LIMA to LAD in MIDCAB technique (**Figure 2**). A total of 15% underwent MV-MIDCAB with LIMA to LAD and saphenous vein (T-Graft) to the diagonal branch (**Figure 3**). The operative and perioperative results are illustrated in **Table 2**. The mean operation time was 2.3 ± 0.8 h. Conversion to sternotomy was necessary in one patient (0.4%) who had myocardial ischemia postoperatively. The RCA could not be treated with PCI. Therefore the patient underwent sternotomy for additional bypass to the right coronary artery (RCA) at the first postoperative day. The applied amount of packed red blood cells (pRBC) were 0.4 ± 0.8 units. The average intensive care unit stay (ICU) were 1 ± 1.2 days. One patient (0.4%) presented with a minor stroke postoperatively. Myocardial infarction was observed in two patients (0.9%) who underwent coronary re-angiography perioperatively and stent intervention of the right coronary artery. There was no operative death. The 30-day mortality was 1.7% (n = 4). Cause of death were multi organ failure (n = 1), low output syndrome (n = 2), and sepsis due to pneumonia (n = 1). Rethoracotomy for bleeding (*via* left thoracotomy approach) was necessary in eight patients (3.4%). Wound revision due to superficial wound infection was required in three patients (1.3%).

Discussion

Minimally invasive direct coronary artery bypass procedure offers a good solution for patients with isolated proximal LAD

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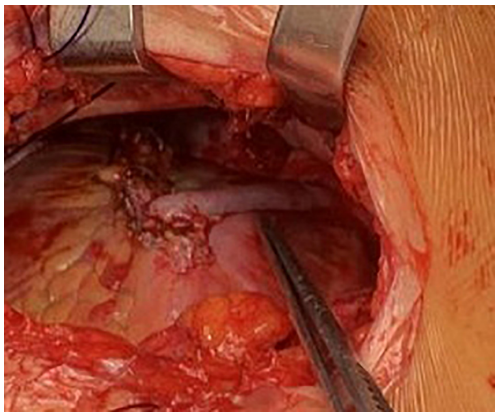

FIGURE 3
Multivessel-MIDCAB, LIMA, to LAD and saphenous vein (T-graft) to diagonal branch anastomoses.

TABLE 2 Operative and postoperative results.

Operative	
One coronary anastomosis	199 (85%)
Two coronary anastomoses	35 (15%)
Operative time (mean, hours)	2.3 ± 0.8
conversion to sternotomy	1 (0.4%)
Total number of coronary anastomoses	269
Postoperative	
Intensive care unit duration (mean, days)	1 ± 1.2
Ventilation time (mean, hours)	6 ± 4
Rethoracotomy	8 (3.4%)
Neurologic event (stroke)	1 (0.4%)
Wound infection	3 (1.3%)
30-day-mortality	4 (1.7%)
Myocardial infarction	2 (0.9%)
pRBC's (mean)	0.4 ± 0.8
Hemoglobin (mean, gr/dl)	11.3 ± 1
Chest tube output in 48 h (mean, ml)	750 ± 300
Hospital length of stay (mean, days)	6 ± 2

pRBC, packed red blood cells.

stenosis. The avoidance of sternotomy and cardiopulmonary bypass (CPB) in the MIDCAB setting has been associated with faster recovery, less bleeding, and fewer transfusions (8). An important strategy for MIDCAB revascularization is a careful patient selection that should be discussed in a heartteam. A LAD diameter < 1.5 mm, diffuse disease, or intramural position of the LAD are reported to be exclusion criteria for MIDCAB (9). Also unfavorable anatomical conditions like obesity, former chest radiation, left thoracotomy (for lung or breast surgery), or stenosis of the left subclavian artery make MIDCAB unsuitable for these patients. Emergent cases and/or hemodynamically instable patients should be also excluded. In the early beginning of the MIDCAB era this technique was predominantly applied in patients with isolated lesions of the LAD. Nowadays it is an attractive option for HCR in multi vessel disease particularly in high-risk patients with several comorbidities. MIDCAB for HCR is reported to be associated with a favorable clinical outcome including lower major adverse cardiovascular and cerebral events (MACCE) and repeat revascularization rates compared with multivessel PCI (10). In our series 40% of the patients underwent HCR. The 30-day mortality was 1.7% (n = 4) that is comparable to the published data of other centers (5, 10–12). Conversion to sternotomy (without cardiopulmonary bypass) was necessary in one patient (0.4%) that is acceptable and similar to published data (5, 10). We observed one (0.4%) neurological event (minor stroke) postoperatively that is low. The applied amount of pRBC were 0.4 ± 0.8 units. The average ICU stay was 1 ± 1.2 days that is short. These findings are similar to the reported results of other MIDCAB performing centers regarding less required blood transfusions and a short ICU stay (5, 13). Although MIDCAB is a challenging technique, it can be performed safely with low complication rates by experienced Off-pump coronary artery bypass (OPCAB) surgeons (11, 13, 14). In selected patients MIDCAB procedure is a good revascularization strategy as described in the following studies. Indja et al. reported that MIDCAB for LAD remains superior to first- or second-generation PCI with DES regarding long-term freedom from myocardial infarction and survival (15). Aziz et al. presented a meta-analysis including 12 studies (1,952 patients) comparing MIDCAB with PCI for single vessel LAD revascularization (16). They could show that there was a higher rate of recurrent angina, need for repeat revascularization and incidence of MACCE with PCI at midterm follow up. Blazek et al. reported the 10-year follow-up results of a randomized trial comparing MIDCAB with bare-metal stenting for stenosis of the LAD (17). They found out that there were no significant differences in the endpoints death and myocardial infarction. However, a significant higher repeat target vessel revascularisation rate was observed in the PCI group (34 vs. 11%, $p < 0.01$). Similar results are described in the propensity matched study of Hannan et al. (18). They observed a significantly lower repeat revascularization rate in patients undergoing CABG vs. PCI with DES (7.09 vs. 12.98%, $p = 0.0007$) in isolated proximal LAD disease at 3-years follow-up. The decision of heartteams plays an important role to enclose the suitable patients for this minimally invasive procedure. There are only a few studies dealing with benefits and late outcomes of heartteam decisions regarding patients with CAD. Domingues et al. report about their experience regarding heartteam recommendations for 1,000 patients with CAD (19). They observed a 5-year mortality rate of 3% for patients with 1 vessel disease with or without proximal LAD involvement. Despite the heartteam recommendation was largely in accordance with the clinical guidelines the timing for treatment could have been further optimized (19). It is mandatory to set up a multidisciplinary heartteam to determine

criteria moving a patient for MIDCAB approach. The surgical view regarding the feasibility of minimally invasive approach with/without hybrid strategy in CAD is essential. Therefore the role of cardiac surgeons in heartteam meetings is crucial. The advantage of a hybrid procedure is the revascularization of multiple territories without a large surgical trauma. To set an example, the RCA territory can be treated with PCI afterward MIDCAB LIMA to LAD has been performed. In the most cases it is not possible to reach the RCA *via* left minithoracotomy in off-pump technique. The rate of hybrid procedures in CAD is increasing. Van den Eynde et al. published the results of a systematic review and meta-analysis regarding HCR versus PCI in 27041 patients (20). They observed that HCR was associated with significantly lower rates of myocardial infarction and target vessel revascularization in comparison to PCI. Therefore HCR strategy is gaining popularity in many experienced heart centers as it is a valid alternative to multivessel PCI.

Minimally invasive cardiac surgery can compete with interventional cardiology and offers outstanding results. Although MIDCAB is technically demanding our postoperative results demonstrate that this procedure is safe and feasible (21). Optimal patient selection and an experienced surgical team are mandatory.

Minimally invasive direct coronary artery bypass for selected patients with proximal LAD lesions and in multi-vessel disease is a safe procedure with a low 30-day mortality and good clinical outcome. Intra- and perioperative application of pRBC's and ICU stay are low. The trauma and incision is small with a good cosmetic result. However, long-term clinical follow up data are necessary to strengthen our thesis.

Limitations

The study has a retrospective design. A control group, e.g., On-pump CABG, was not added. Follow-up data are not included yet as further investigations are ongoing.

Data availability statement

The original contributions presented in this study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving human participants were reviewed and approved by the University Hospital Bonn. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

Author contributions

NM and EA analyzed the data. NM, EA, and SS structured the manuscript giving contribute to tables, figures, and text editing. FB revisited the article implementing the final manuscript form. All authors contributed to the manuscript production and in the final revision.

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The abstract of this manuscript was presented in part at the annual meeting of the German Society of Thoracic-, Heart- and Vascular Surgery in February 2022 (21).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Do obese patients with type A aortic dissection benefit from total arch repair through a partial upper sternotomy?

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Background: Minimal research has been performed regarding total arch replacement through partial upper sternotomy in patients with acute type A aortic dissection who are obese, and the safety and feasibility of this procedure need to be further investigated. The present study investigated the potential clinical advantages of using a partial upper sternotomy versus a conventional full sternotomy for total arch replacement in patients who were obese.

Methods: This was a retrospective study. From January 2017 to January 2020, a total of 65 acute type A aortic dissection patients who were obese underwent total arch replacement with triple-branched stent graft. Among them, 35 patients underwent traditional full sternotomy, and 30 patients underwent partial upper sternotomy. The perioperative clinical data and postoperative follow-up results of the two groups were collected, and the feasibility and clinical effect of partial upper sternotomy in total arch replacement were summarized.

Results: The in-hospital mortality rates of the two groups were similar. The total operative time, cardiopulmonary bypass, aortic cross-clamp, cerebral perfusion, and deep hypothermic circulatory arrest times were also similar in both groups. The thoracic drainage and postoperative red blood cell transfusion volumes in the partial upper sternotomy group were significantly lower than those in the full sternotomy group. Mechanical ventilation time was shorter in the partial upper sternotomy group than that in the full sternotomy group. Additionally, the incidences of pulmonary infection, hypoxemia, and sternal diaphoresis were lower in the partial upper sternotomy group than those in the full sternotomy group.

Conclusion: This study showed that total arch replacement surgery through a partial upper sternotomy in patients with acute type A aortic dissection who are obese is safe, effective, and superior to full sternotomy in terms of blood loss, postoperative blood transfusion, and respiratory complications.

KEYWORDS

acute aortic dissection, obesity, partial upper sternotomy, total arch replacement, triple-branched stent

1. Introduction

With recent economic development, living standards have improved significantly. However, the lack of proper exercise and the excessive intake of unhealthy food have led to increased obesity, a condition that can lead to lifestyle and health difficulties. Individuals who are obese often have a combination of hypertension, diabetes, hyperlipidemia, and other risk factors closely related to cardiovascular disease (1, 2). Some studies have reported that obesity is one of the causative factors for the development of type A aortic dissection (AAD) (3). As a result, the proportion of patients with AAD who are obese [Body Mass Index (BMI) ≥30 kg/m2] is continuously increasing. Obesity increases the duration of ventilator use after cardiovascular surgery and can lead to complications such as hypoxemia or poor wound healing, prolonging hospital stays. Since the 1990s, the surgical pathway using partial upper sternotomy (PUS) has been widely used in various cardiac surgeries (4–7). Due to the physiological characteristics of patients who are obese and the urgency of the surgery, such patients have a slow recovery of respiratory function postoperatively and are prone to complications such as pulmonary infection and hypoxemia. Therefore, we believe that total arch replacement (TAR) surgery using PUS has significant benefits for patients with AAD who are obese.

The aim of this study was to investigate whether using PUS is safe and feasible in patients with type A aortic coarctation who are obese and if the potential benefits are associated with the partial incision of PUS versus the full incision required for traditional full sternotomy (FS) in TAR.

2. Materials and methods

2.1. Patients

This was a retrospective study. Data was collected from the medical charts of patients with AAD treated using TAR between January 2017 and January 2020. Sixty-five patients were categorized into the FS group (35 cases) or the PUS group (30 cases) according to the sternal incision during thoracotomy. All patients met the following criteria: (1) preoperative BMI ≥ 30 kg/m2; (2) acute type A aortic dissection confirmed by aortic computed tomography angiography (CTA); (3) underwent TAR using triple-branched stent graft; and (4) surgery was emergent. The exclusion criteria were: (1) second open-heart surgery; (2) combination of severe trauma or congenital sternal malformation; (3) combination of severe chronic obstructive pulmonary disease (COPD) or severe respiratory insufficiency; (4) need for management of mitral or tricuspid valve lesions during the same period; and (5) need for coronary artery bypass grafting during the same period. Until December 2018, all obese AAAD were treated through the operative approach of FS. Since January 2019, PUS has become the standard operative approach for all obese AAAD. Patients who received PUS did not receive additional preoperative evaluation after excluding the relevant contraindications.

In this study, COPD was defined as chronic bronchitis or emphysema characterized by airflow obstruction and severe respiratory insufficiency was defined as a $PaO_2 < 60$ mmHg and a $PaCO_2 > 50$ mmHg due to severe disturbance of external respiratory function (8, 9).

All surgeries were performed by the same senior surgeon using the same medical team. The ethics committee of the Union Hospital of Fujian Medical University approved the study. Written informed consent was not required due to the retrospective nature of the study.

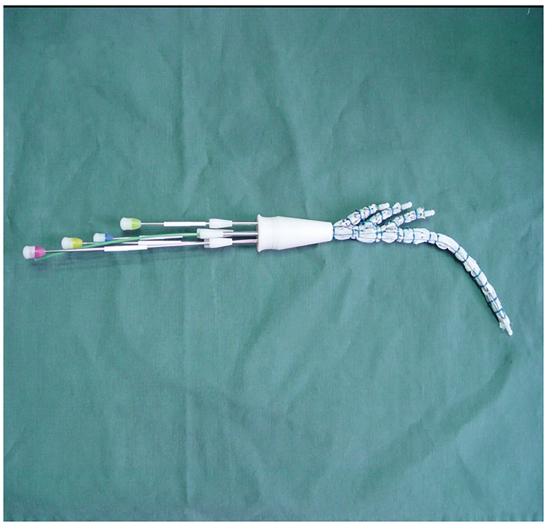

FIGURE 1
The modified triple-branched stent graft is comprised of a main graft and three sidearm grafts.

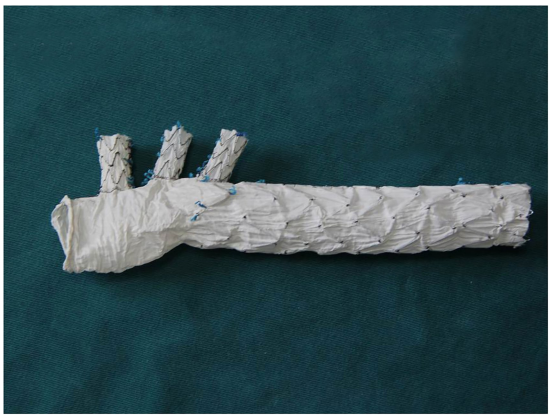

FIGURE 2
The modified triple-branched stent graft is comprised of a main graft and three sidearm grafts.

2.2. Triple-branched stent graft

The triple-branched stent graft, independently developed by Professor Chen, is a branch-integrated graft composed of a self-expanding nickel-titanium alloy stent and a polyester vascular graft fabric. The triple-branched stent graft includes one main stent and three sidewall stent grafts (Figures 1, 2) (10, 11).

Abbreviations: AAD, type A aortic dissection; PUS, partial upper sternotomy; TAR, total arch replacement; FS, full sternotomy; CPB, cardiopulmonary bypass; ACC, aortic cross-clamp; DHCA, deep hypothermic circulatory arrest.

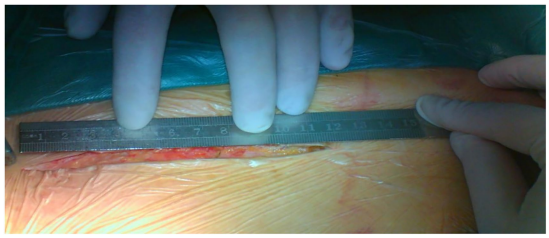

FIGURE 3
The length of the incision in partial upper sternotomy.

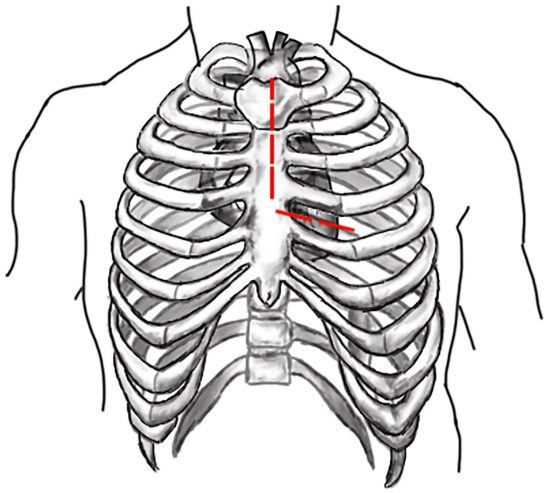

FIGURE 4
Schematic diagram of "L" shaped incision in partial upper sternotomy.

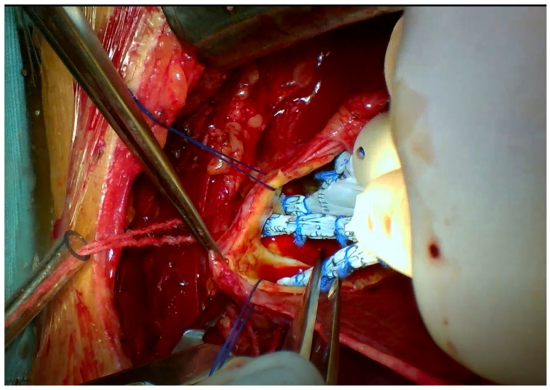

FIGURE 5
Partial upper sternotomy incision for total arch repair of acute type A aortic dissection.

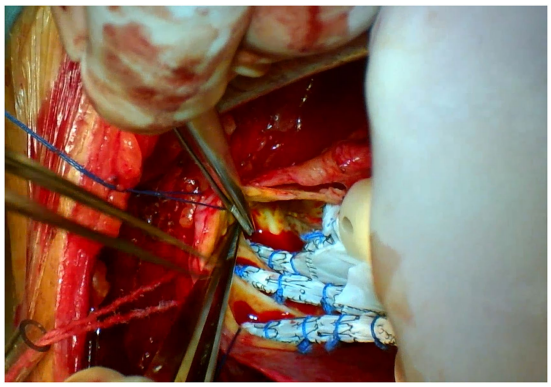

FIGURE 6
Partial upper sternotomy incision for total arch repair of acute type A aortic dissection.

2.3. Surgical technique for FS and PUS

Both surgeries are performed under general anesthesia. Arterial pressure monitoring of upper and lower extremities is established routinely, and echocardiographic probes are routinely placed in the esophagus. In FS, the skin incision extends longitudinally from the superior sternal fossa to the xiphoid process (a length of approximately 18-20 cm), and the sternum is completely divided. In PUS, the skin incision extends longitudinally from the sternal notch to the fourth intercostal space (ICS) (a length of approximately 8-10 cm; Figure 3). After the surgeon identifies the fourth ICS, the sternum is sawed to the ICS and to the left, creating an "L"-shaped incision (Figure 4). If the incision is not well exposed to the surgical field, it can be extended to the fifth ICS to improve clear exposure. The incision exposes the ascending aorta and the root of the aorta, the superior vena cava, the right atrial appendage, part of the right atrium, and the top of the left atrium. Establishment of systemic cardiopulmonary bypass (CPB) is obtained through a right atrial venous catheter and the femoral and right axillary arteries. After bypass, the body temperature is carefully decreased; when the nasopharyngeal temperature decreases to 32°C, the ascending aorta is blocked above the junction of the sinus canal. The cardioplegia pharmaceutical is directly injected into the coronary vein orifice for cardiac arrest and myocardial protection. If the condition of the aortic root requires attention, the repair is performed using procedures such as aortic sinus plasty and the Bentall. After the aortic root reconstruction is completed, the repaired root is sutured continuously using a pedestrian Dacron vessel. When the nasopharyngeal temperature reaches 25°C, circulatory arrest begins followed by the establishment of unilateral antegrade cerebral perfusion through the right axillary artery cannulation. An oblique incision is made near the small bend of the aortic arch, and the main part of the triple-branched stent graft is inserted into the true cavity of the aortic arch and the proximal descending aorta. Then, each lateral arm graft is located in the aortic branch (Figures 5, 6). Finally, the end of the triple-branched stent graft and the artificial polyester blood vessel are anastomosed continuously to complete the operation (12).

2.4. Statistical analysis

We used SPSS version 19.0 for Windows software for all statistical analyzes. Continuous variables with a normal distribution are expressed as mean ± standard deviation (SD) and compared using a Student t-test; otherwise, they are expressed as median (Q25, Q75) and compared with a Mann–Whitney U test. Categorical data were shown as number (%) and analyzed using the chi-square test or Fisher's exact test as appropriate. p-value <0.05 was considered statistically significant. The

TABLE 1 Comparison of preoperative data between the two groups (n=65).

Valuables	FS group (n=35)	PUS group (n=30)	p-value
Demographic and baseline risks			
Age (years)	52.6 ± 5.7	51.7 ± 8.2	0.615
Body mass index (kg/m^2)	30.7 ± 0.9	30.8 ± 1.0	0.637
Male gender (n, %)	24 (68.6%)	19 (63.3%)	0.656
Hypertension (n, %)	29 (82.9%)	24 (80.0%)	0.767
Diabetes mellitus (n, %)	6 (17.1%)	7 (23.3%)	0.534
Smoking history (n, %)	19 (54.3%)	13 (43.3%)	0.379
Drinking history (n, %)	7 (20.0%)	4 (13.3%)	0.475
Preoperative LVEF (%)	61.3 ± 9.0	62.0 ± 5.2	0.702
Preoperative complications			
Chronic obstructive pulmonary disease (n, %)	1 (2.9%)	1 (3.3%)	1.000
Moderate/severe pericardial effusion (n, %)	3 (8.6%)	0	0.243
Preoperative renal insufficiency (n, %)	4 (11.4%)	2 (6.7%)	0.678
Preoperative hepatic dysfunction (n, %)	6 (17.1%)	4 (13.3%)	0.937
Acute aortic regurgitation (n, %)	10 (28.6%)	8 (26.7%)	0.864
Pericardial tamponade (n, %)	2 (5.7%)	0	0.495
Malperfusion syndrome (n, %)	12 (34.3%)	6 (20.0%)	0.199
Transient cerebral ischemia (n, %)	1 (2.9%)	0	1.000

Continuous variables were present as mean ± standard deviation (SD). Categorical variables were shown as number (%). The Student t test or Man-Whitney U test was used for continuous variables, and Chi-square test used for categorical variables. LVEF, left ventricular ejection fractions.

TABLE 2 Comparison of intraoperative conditions between the two groups (n=65).

Valuables	FS group (n=35)	PUS group (n=30)	p-value
Aortic root procedure			0.965
No treatment (n, %)	4 (11.3%)	3 (10.0%)	
Sinus plasty (n, %)	20 (57.1%)	19 (63.3%)	
Bentall procedure (n, %)	10 (28.6%)	8 (26.7%)	
David procedure (n, %)	1 (2.9%)	0	
Intraoperative time			
Total operative time (min)	292.1 ± 48.2	283.3 ± 25.5	0.357
Cardiopulmonary bypass time (min)	140.5 ± 19.6	136.0 ± 26.6	0.437
Aortic cross-clamp time (min)	46.2 ± 13.4	44.1 ± 12.8	0.518
Cerebral perfusion time (min)	9.8 ± 2.2	9.3 ± 2.0	0.308
DHCA time (min)	2.0 (2.0,4.0)	2.0 (2.0,3.0)	0.589

Continuous variables were present as mean ± standard deviation (SD) or median (Q25, Q75). Categorical variables were shown as number (%). The Student t test or Man-Whitney U test was used for continuous variables, and Chi-square test used for categorical variables. DHCA, deep hypothermic circulatory arrest.

survival rate was calculated by Kaplan–Meier survival curve, and Log-Rank test was used to test whether there was any difference between groups.

3. Results

Between January 2017 and January 2020, 65 patients with AAD who were admitted to our department met the study criteria. Of these, 35 individuals were treated using FS and 30 individuals were treated using PUS. The preoperative baseline information such as age, gender, preoperative BMI, and preoperative cardiac function were similar between the two groups, and the preoperative underlying disease and comorbidities were approximately the same, with no statistically significant differences between the two groups (Table 1).

No patient required conversion from PUS to FS. The total operative, CPB, aortic cross-clamp (ACC), cerebral perfusion, and deep hypothermic circulatory arrest (DHCA) times were approximately the same in both groups. There were no significant differences in the management of the aortic root between the two groups (Table 2).

The postoperative results of the two groups are shown in Table 3. The mean quantity of thoracic drainage volume at 48 h following surgery (572.9 ± 87.6 ml vs. 472.7 ± 115.5 ml, p < 0.001) and postoperative red blood cell transfusion volume (697.1 ± 179.4 ml vs. 503.3 ± 145.6 ml, p < 0.001) were significantly lower in the PUS group than those in the FS group. The postoperative numeric rating scale pain score was lower [5.5 (5.0, 6.8) vs.

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TABLE 3 Comparison of postoperative results between the two groups (n=65).

Valuables	FS group (n=35)	PUS group (n=30)	p-value
30-d mortality (%)	3 (8.6%)	2 (6.7%)	1.000
ICU stay time (day)	6.5 ± 4.8	5.9 ± 5.0	0.652
Total hospital stay time (day)	20.5 ± 7.8	18.5 ± 5.3	0.223
Mechanical ventilation time (h)	47.3 ± 13.7	40.1 ± 12.7	0.034
Thoracic drainage (ml/48 h)	572.9 ± 87.6	472.7 ± 115.5	<0.001
Red blood cell transfusion (ml)	697.1 ± 179.4	503.3 ± 145.6	<0.001
Postoperative NRS score	5.5 (5.0,6.8)	4.0 (3.0,5.0)	<0.001
Postoperative complications			
Pulmonary infection (n, %)	21 (60.0%)	10 (33.3%)	0.032
Hypoxemia (n, %)	9 (25.7%)	2 (6.7%)	0.041
Permanent neurological dysfunction (n, %)	2 (5.7%)	0	0.495
Transient neurological dysfunction (n, %)	1 (2.9%)	2 (6.7%)	0.591
Low Cardiac Output Syndrome (n, %)	2 (5.7%)	1 (3.3%)	1.000
Acute renal injury (n, %)	5 (14.3%)	4 (13.3%)	1.000
Hepatic dysfunction (n, %)	9 (25.7%)	5 (16.7%)	0.376
Sepsis (n, %)	2 (5.7%)	1 (3.3%)	1.000
Secondary thoracotomy (n, %)	2 (5.7%)	0	0.495
Multiple organ failure (n, %)	3 (8.6%)	1 (3.3%)	0.618
Sternum dehiscence (n, %)	6 (17.1%)	0	0.027
Incision infection (n, %)	5 (14.3%)	1 (3.3%)	0.205

Continuous variables were present as mean ± standard deviation (SD) or median (Q25, Q75). Categorical variables were shown as number (%). The Student t test or Man-Whitney U test was used for continuous variables, and Chi-square test used for categorical variables. NRS, numerical rating scale.

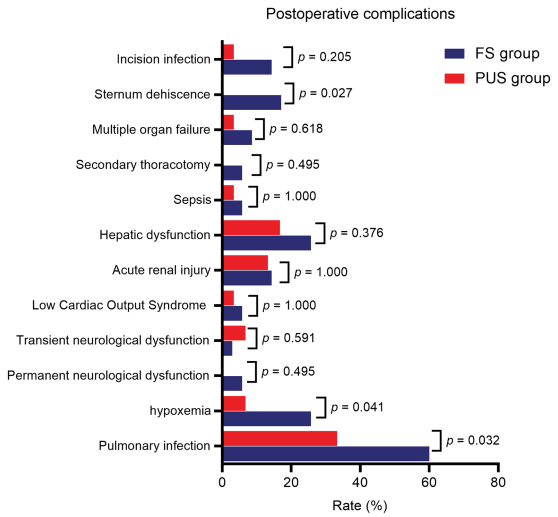

FIGURE 7
Postoperative complications of patients in two groups.

4.0 (3.0, 5.0), p<0.001], and the postoperative mechanical ventilation time was significantly shorter (47.3 ± 13.7 h vs. 40.1 ± 12.7 h, p=0.034) in the PUS group than those in the FS group. The ICU stay time (5.9 ± 5.0d vs. 6.5 ± 4.8d, p=0.652) and postoperative hospital stay time (18.5 ± 5.3d vs. 20.5 ± 7.8d, p=0.223) in the PUS group were shorter than those in the FS group; however, the differences were not significant. Among the postoperative complications, the incidences of pulmonary infection (33.3% vs. 60.0%, p=0.032), hypoxemia (6.7% vs. 25.7%, p=0.041), and sternum refixation (0 vs. 17.1%, p=0.027) were significantly lower in the PUS group than those in the FS group. The incidences of low cardiac output syndrome, hepatic dysfunction, acute renal injury, sepsis, multiple organ failure, and nervous system dysfunction were similar between the two groups. Furthermore, there was no significant difference in the incidence of secondary thoracotomy for hemostasis and surgical wound infection between the two groups (Figure 7).

The postoperative follow up of the two groups is shown in Table 4. A total of 60 patients were discharged successfully. Up to January 2022, 56 patients were followed up by means of outpatient revisit appointments, telephone, and mail, with a follow-up rate of 93.3% and an average follow-up time of 32.4 ± 8.6 months. The follow-up results of thoracic and abdominal aorta CTA and echocardiography showed no significant difference between the two groups in the closure rate of the false cavity (p=1.000), and the left ventricular ejection fraction was almost the same 2 years after surgery (p=0.230). There was no significant difference between the postoperative survival rate of each time period between the two groups. We combined the survival rate and the postoperative follow-up results to create a cumulative survival function diagram with death as the end point (Figure 8). As Figure 8 shows, there was no significant difference in the early and medium-term survival rate between the two groups (p=0.481).

4. Discussion

Our results showed that PUS is as safe and effective as FS in patients who are obese. There was no difference in total operative, CPB, ACC, cerebral perfusion, and DHCA times between the two groups. There was

TABLE 4 Comparison of postoperative follow-up between the two groups.

Valuables	FS group	PUS group	*p*-value
Closure rate of false cavity (2-years)	86.2%	88.5%	1.000
LVEF (2-years) (%)	60.4 ± 4.4	59.0 ± 3.7	0.230
3-month survival rate	100%	100%	1.000
6-month survival rate	93.3%	100%	0.494
1-years survival rate	90.0%	96.2%	0.615
2-years survival rate	86.7%	92.3%	0.675

Continuous variables were present as mean ± standard deviation (SD). Categorical variables were shown as number (%). The Student t test or Man-Whitney *U* test was used for continuous variables, and Chi-square test used for categorical variables. LVEF, left ventricular ejection fractions.

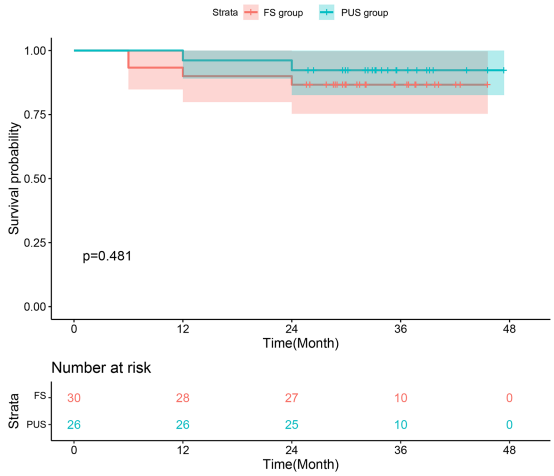

FIGURE 8
Kaplan–Meier estimates of survival for patients with acute type A aortic dissection who underwent total arch repair with triple-branched stent graft.

also no significant difference in the incidences of secondary thoracotomy for hemostasis, surgical wound infection, low cardiac output syndrome, hepatic dysfunction, acute renal injury, multiple organ failure, and nervous system dysfunction between the two groups. The ICU and hospital stay times were also similar. Most importantly, our results showed that postoperative thoracic drainage and red blood cell transfusion volumes were significantly decreased in the PUS group. Moreover, the incidences of pulmonary infection, hypoxemia, and sternal dehiscence were decreased in the PUS group. Through follow up, we found that the closure rate of the false cavity, the cardiac function, and the early and medium-term survival rates were similar between the two groups.

With the rapid development of minimally invasive surgery, minimally invasive cardiac surgery has become a trend. Since 1996, the partial sternotomy approach has been used in some routine cardiac operations, such as heart valve replacement (13). Recently, PUS has been more widely used in cardiovascular surgeries. In some technologically mature heart centers, PUS has become a routine approach for aortic valve, ascending aorta, and semi-arch replacements (6, 7).

At present, the global population is becoming more and more obese, and the obesity rate continues to rise (14). Due to the large population base and an obesity rate of more than 50%, China has become the largest obese country worldwide (15). The proportion of patients with AAD who are obese also continues to increase. Xie et al. believe that extensive repair of acute AAD using PUS is safe and does not increase the postoperative mortality or risk of serious complications (16). Our results further support this view.

According to Brinkman et al. (17), patients who are obese that have hypertrophy of the chest wall provide challenges for surgeons in terms of achieving adequate surgical field exposure during surgery. Therefore, when using partial sternotomy for cardiovascular surgery in patients who are obese, surgeons will need to be cognizant of the potential issue of inadequate surgical field exposure. Our center independently developed a triple-branched stent graft (10–12). Through the placement of the graft to replace the complex vascular anastomosis in the traditional TAR, the position of the anastomosis of the distal arch vessels in the traditional operation is moved upward to the lesser curved side of the aorta, which is beneficial to the vascular anastomosis operation. This approach also reduces the number of vascular anastomoses, thus avoiding the surgical field exposure problem in patients who are obese.

The sternotomy length is shortened in PUS, reducing the extent of the surgical wound and the risk of postoperative bleeding. Our results showed that postoperative thoracic drainage and red blood cell transfusion volumes were significantly decreased in the PUS group compared to those in the FS group, which is consistent with the advantages of partial sternal incision reported in previous studies (18–21). Due to these advantages, the thoracic drainage tube can be removed earlier in patients who have undergone PUS, which is conducive to early recovery of out-of-bed activities. In addition, the postoperative blood transfusion volume is reduced in PUS; therefore, transfusion-related complications caused by massive blood transfusion are effectively avoided.

The incision in PUS encompasses only part of the upper sternum; the lower sternum remains intact and the overall structure of the thorax is maintained. In patients who are obese, the hypertrophy of the chest wall and the upward shift of the diaphragm increase the pressure in the chest cavity, which in turn causes obstruction of the small pulmonary airways and can lead to difficulty in ventilation and subsequently hypoxia. Furthermore, obesity increases the blood volume in the body, which can easily lead to congestion of lung tissue and decrease lung compliance. Therefore, patients who are obese are prone to difficulty in lung re-expansion in the early postoperative stages. The potential of delayed extubation and the need for longer mechanical ventilation increase the risk of respiratory tract infection. Our results show that PUS can significantly shorten the mechanical ventilation time, significantly reduce the incidences of postoperative pulmonary infection and hypoxemia, and reduce the effect of thoracotomy on respiratory function. This is particularly beneficial for patients who are obese.

Sternal dehiscence is a rare but serious complication after thoracotomy. Patients who are obese have a higher risk of sternal dehiscence due to poor chest compliance and high sternal tension (22). In this study, 6 cases of

sternal dehiscence occurred postoperatively in the FS group. In addition, 5 cases in this group were complicated by the comorbidity of type 2 diabetes, and 2 cases had significantly longer mechanical ventilation times postoperatively. These results are consistent with the risk factors of sternal dehiscence reported in the literature (23). There was no sternal dehiscence in the PUS group in our study. This may be largely due to the PUS group having complete sternal structure, reducing excessive tension, thereby avoiding sternal fracture. Hence, mechanical ventilation time was shortened, reducing the effect of positive pressure ventilation on sternal stability and decreasing the probability of sternal dehiscence.

We believe that PUS as a component of FS should be a relatively familiar approach for cardiac surgeons. The only differences between the two approaches are in the mode of thoracotomy and the extent of sternotomy. Therefore, PUS does not significantly change the cardiovascular surgeon's operating habits. To perform PUS in patients with AAAD who are obese requires the chief surgeon to master all aortic root management methods and be proficient in the use of modified triple-branched stent grafts for TAR. In PUS, the surgical operative space is smaller, which poses more of a challenge to the surgical skills of the chief surgeon and the knowledgeable cooperation of assistant doctors. Therefore, it is necessary for surgeons and assistants to study both procedures extensively and have opportunities for practical experience using PUS in patients who are not obese. This will enhance the success of using PUS in patients who are obese.

This study has some limitations. First, this was a single-center retrospective study. Due to the small sample size, our results may be one-sided. Second, the interval between the operative years (2017–2020) of the two groups is relatively long, and there may have been potential differences in treatment plans and operative techniques. However, this may have been avoided because the same experienced surgeon performed all operations in this study.

4.1. Conclusion

Total arch replacement of acute AAD through PUS is a safe and feasible procedure. Compared to TAR through FS, PUS is associated with fewer respiratory complications, better recovery of respiratory function, less blood loss, and improved thoracic stability.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving human participants were reviewed and approved by the ethics committee of the Union Hospital of Fujian Medical University. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

Author contributions

L-FX, JH, and LC designed the study, participated in the operation, and drafted the manuscript. L-FX and JH collected the clinical data and performed the statistical analysis. LC, Z-HQ, Q-SW, H-QG, and D-BJ provide technical support. All authors have read and approved the final manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Twenty-five year experience with aortic valve-sparing root replacement in a single teaching center

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Objectives: Aortic valve-sparing root replacement (AVSRR) is a technically demanding procedure. In experienced centers it offers excellent short- and long-term results, making the procedure an attractive alternative for aortic root replacement especially in young patients. The aim of this study was to analyze long-term results of AVSRR using the David operation in our institution over the last 25 years.

Methods: This is a single-center retrospective analysis of outcomes of David operations performed in a teaching institution not running a large AVSRR-program. Pre-, intra- and postoperative data were collected from the institutional electronic medical record system. Follow-up data were collected through direct contact of the patients and their cardiologists/primary care physicians.

Results: Between 02/1996 and 11/2019, 131 patients underwent David operation in our institution by a total of 17 different surgeons. Median age was 48 (33–59), 18% were female. Elective surgery was performed in 89% of the cases, 11% were operated as emergency in the setting of an acute aortic dissection. Connective tissue disease was present in 24% and 26% had a bicuspid aortic valve. At hospital admission 61% had aortic regurgitation grade ≥3, 12% were in functional NYHA-class ≥III. 30-day mortality was 2%, 97% of the patients were discharged with aortic regurgitation ≤2. In 10-year follow-up, 15 (12%) patients had to be re-operated because of root-related complications. Seven patients (47%) received a transcatheter aortic valve implantation, 8 (53%) required surgical replacement of the aortic valve or a Bentall-De Bono operation. Estimated reoperation-free survival at 5 and 10 years was 93.5% ± 2.4% and 87.0% ± 3.5%, respectively. Subgroup analysis showed no differences in reoperation-free survival for patients presenting with a bicuspid valve or preoperative aortic regurgitation ≥3. However a preoperative left ventricular end diastolic diameter of ≥5.5 cm was associated with worse outcome.

Conclusion: David operations can be performed with excellent perioperative and 10-year follow-up outcomes in centers not running large AVSRR-programs.

KEYWORDS

aortic valve sparing surgery, aortic root reimplantation, aortic regurgitation (AR), aortic aneurysm (AA), David operation and David procedure, david operation, david procedure

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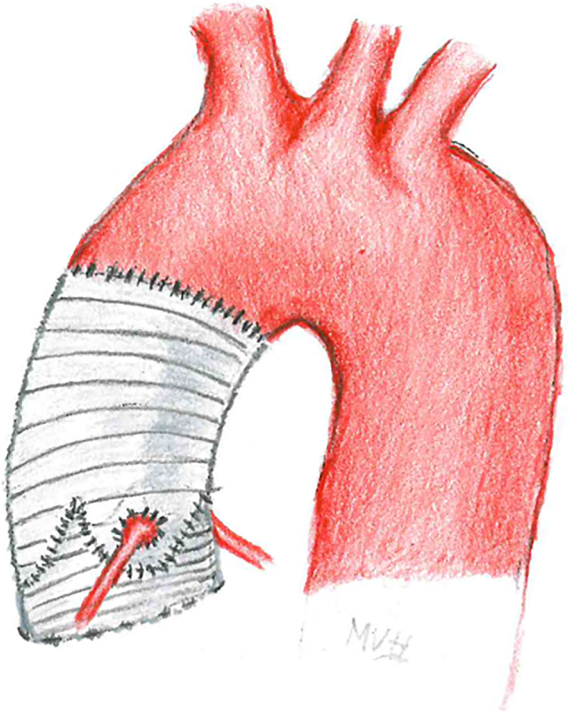
Introduction

In patients with aortic root aneurysm and aortic valve (AV) dysfunction root- and AV-replacement with a composite valved graft, as introduced by Bentall and De Bono in 1968, has proven to be a safe and durable procedure (1). However, younger patients with aortic root-dilatation and a structurally normal AV may benefit from an aortic valve-sparing root replacement (AVSRR), since valve replacement in these cases is inevitably associated with life-long oral anticoagulation, an increased risk of infective endocarditis and redo-surgery in case a tissue valve has been selected.

To preserve the AV in case of a dilated sinus of Valsalva, several surgical techniques have been introduced during the last three decades (2). In the remodeling-technique, such as the Yacoub-procedure, the vascular prosthesis to replace the aortic root is trimmed to provide three artificial sinuses, while the annulus is not stabilized as well as in the reimplantation technique. In the latter, the native aortic valve is resuspended into the vascular prosthesis and the aortic annulus is stabilized through sub-annular sutures. The Yacoub-procedure seems to offer very nice functional results with a preserved elasticity of the aortic root and of the native aortic annulus. This advantage may be outweighed through a late enlargement of the aortic annulus leading to progressive aortic regurgitation, particularly in patients with underlying connective tissue disease, for whom the Yacoub-technique is not recommended. The reimplantation technique, originally described by David et al. in 1992 (3, Central image) allows less expansion of the annulus during the cardiac cycle (4), but offers excellent short- and long-term-results when performed in experienced centers (5).



CENTRAL IMAGE
Aortic valve sparing root replacement – David operation.

Short- and long-term analyses for both mentioned AVSRR-procedures have mostly been reported from high-volume centers running larger AVSRR programs in which the procedures are performed by few specialized surgeons. Little is known if these technically demanding procedures can be performed with similar results in a mid-volume teaching center. The aim of this study was to analyze the long-term-results of AVSRR using the David operation in our institution over the last 25 years.

Methods

Study design

This is a retrospective analysis from a single-center's database reporting the results of patients that were treated with an aortic valve sparing root replacement as originally described by David et al. in 1992 (3).

Ethics

The study design was approved by the institutional review board/ethics committee (KEK-ZH # 2015-0292). Informed consent was waived due to the retrospective nature of the study and institutional database approval.

Operative technique

All patients underwent AV reimplantation into a tubular graft (3). Minor modifications of the procedure, e.g., plication of the free edge of the leaflets at the presence of valve-prolapse, were left at the discretion of the operating team (6). Additional procedures were performed whenever indicated and included coronary bypass-surgery, additional valve-surgery or (partial) replacement of the aortic arch. Despite technically possible through minimally invasive access (7), for the sake of optimal exposure and considering the potential need for concomitant procedures, all David operations in this study were performed through a full sternotomy.

Indication for surgery

Indication for aortic root replacement was based on elective echocardiographic assessment for chronic findings or on intraoperative transesophageal echocardiography in case of an emergency-situation such as acute aortic dissection. Indication for AVSRR was made intraoperatively in these cases. Generally, patients with normal valve opening, absence of significant valve-calcifications and aortic root enlargement were identified as potential candidates for a David operation.

Inclusion/exclusion criteria

Attempted David operations with intraoperative conversion to a Bentall—De Bono operation were not included in this analysis.

Definitions

Indication for surgery was based on the ESC/EACTS guidelines valid on the respective date of admission (8). Valve regurgitation was assessed by transthoracic or transesophageal echocardiography as recommended in the ESC guidelines on the management of valvular heart disease. The anatomy of the AV (bicuspid or tricuspid) was assessed preoperatively, whenever possible, but had to be confirmed intraoperatively in order to be classified as tri- or bicuspid. A partial fusion of two leaflets was classified as a bicuspid valve when described so in the operating report.

Samples of the aortic wall were sent for histopathological analysis and in certain cases for genetic testing for connective tissue-disease (CTD). Patients were classified to have a CTD if diagnosis was highly suggestive due to concomitant disease or presenting phenotype, hereditary predisposition or if CTD was confirmed by genetic testing. Acute type A aortic dissection was defined as in the mentioned guidelines above (8).

Re-operation during follow-up was defined as surgery related to the aortic valve or aortic root and included transcatheter aortic valve implantation (TAVI) as well as conventional surgical procedures. Interventions beyond the aortic arch, e.g., thoracic endovascular aortic repair (TEVAR) in case of residual dissection or dilatation of the descending thoracic aorta, were not considered as reoperations. Early death was defined as 30-day or in-hospital death with interhospital transfer not considered as hospital discharge.

Data collection

All patients had pre-operative assessment by transthoracic and/or transesophageal echocardiography as well as by computed tomography or magnetic resonance imaging. Severity of pre-operative aortic valve regurgitation was abstracted from echocardiography reports and in case of ambiguity, echocardiographic studies were reviewed for the purpose of this study. Pre-, intra- and postoperative data were collected from the institutional electronic medical record system. Clinical follow-up data were collected from outpatient clinic visits or by directly contacting the patients and their primary care physicians, echocardiographic follow-up data were mainly derived from transthoracic echocardiography performed by in-house or patients' private cardiologists. The database was locked as of December 2019 for completion of follow-up.

Outcomes of interest

Main goal of this study was to describe reoperation free long-term survival after AVSRR in our center. Short- and long-term performance of the reimplanted aortic valve was defined as secondary outcome of interest. Potential risk-factors for adverse outcomes (in-hospital mortality, long-term-mortality, reoperation) were investigated in subgroup analyses.

Statistical analyses

Standard descriptive statistics were used to summarize data. Continuous and discrete variables are presented as means with standard deviation or median and 25%/75% Quartile when not normally distributed. Categorical and ordinal variables are presented as absolute numbers and proportions.

Survival and freedom from events were calculated according to the Kaplan–Meier method. The log-rank test with Kaplan–Meier curves was used for group-survival-comparisons. The estimated survival of a patient started at the time of the operation and ended at the time of death/reoperation (event) or the latest known follow-up (censored). Cox-regression models were used for risk factor analysis to confirm significant log-rank tests.

A two-sided p-value <0.05 was considered statistically significant. Statistical analyses were performed using the SPSS 25.0 software package (SPSS, Inc., IL, United States).

Results

Preoperative data

Between February 1996 and November 2019, 131 patients (18% female) underwent AVSRR using the David technique by a total of 17 different surgeons [Median of surgeries performed per surgeon: 4 (1–13)]. Median age at time of surgery was 48 years (38–59). In a total of 31 (24%) patients CTD was identified as the underlying cause of aortic root dilatation. Three different CTD were observed in this study: Marfan's disease, Loeys-Dietz and Ehlers-Danlos syndromes. The majority of operations were elective procedures (89%) but emergency operation for acute type A dissection (ATAAD) comprised 11% of cases. In 13 patients (10%), AVSRR was performed as a cardio-thoracic reoperation: five patients had prior surgery for coarctation of the aorta, one patient had surgical repair for an acute type B aortic dissection, three patients suffered progressive root dilatation after supracoronary replacement of the ascending aorta, one patient had progressive regurgitation after Yacoub-remodeling, three patients had severe regurgitation of the neo-aortic valve after Ross-procedure. A bicuspid valve (Sievers type 0/1/2) (9) was diagnosed in 26% of the patients. Eighty-eight percent of the patients were asymptomatic or had only minor symptoms (NYHA-functional class I & II) prior to hospital admission, moderate or severe aortic regurgitation was present in 61% of the patients. The mean diameter of the sinus of Valsalva was 50 ± 7 mm, the mean diameter of the ascending aorta at the level of the pulmonary bifurcation was 47 ± 13 mm respectively. Data on baseline characteristics, comorbidities and measurements from preoperative echocardiography/computed tomography are presented in **Table 1**.

Intraoperative data

All 131 patients underwent successful aortic valve reimplantation. Mean cardiopulmonary bypass and arrest times were 186 ± 73 and 135 ± 48 min respectively. A central suture-plication at the *nodulus Arantii* was performed in 39 patients (30%). A Dacron-graft from 22 to 32 mm in diameter was used for AVSRR. Sixteen patients (12%) required an open distal anastomosis during a short period of circulatory arrest with antegrade cerebral perfusion. Additional valve repair/replacement

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TABLE 1 Preoperative characteristics.

Age (years)	48 (33–59)
Gender	
Male	107 (82%)
Female	24 (18%)
Comorbidities	
Connective tissue disease	30 (23%)
Insulin dependent DM	2 (2%)
Arterial Hypertension	53 (40%)
Peripheral artery disease	4 (3%)
COPD	3 (2%)
Cerebrovascular event	7 (5%)
Acute Type A aortic dissection	15 (11%)
Redo heart-surgery	13 (10%)
Laboratory findings	
Preoperative Creatinine (μmol/L)	82 ± 16
NYHA functional class	
NYHA I	91 (72%)
NYHA II	20 (16%)
NYHA III	11 (9%)
NYHA IV	4 (3%)
Echo- and CT-data	
Cuspidity	
Bicuspid valve	34 (26%)
Tricuspid valve	97 (74%)
Aortic regurgitation	
None (0)	12 (9%)
Trivial (1)	15 (12%)
Mild (2)	23 (18%)
Moderate (3)	50 (39%)
Severe (4)	29 (22%)
LVEF (%)	60 ± 8
LV-Diameter	
LVESD (mm)	36 ± 8
LVEDD (mm)	56 ± 9
Aortic diameters	
Annulus (mm)	27 ± 5
Aortic root (mm)	50 ± 7
ST-junction (mm)	44 ± 9
Ascending aorta (mm)	47 ± 13

(3 mitral repair, 1 mitral replacement, 1 pulmonary homograft) was needed in 5 patients (4%), concomitant aortocoronary bypass was performed in 9 patients (7%).

Early postoperative outcomes

Three patients (2%) died in the early postoperative period. One patient suffered from hypoxic brain damage in the setting of an ATAAD, one patient died due to an acute bleeding from the aortic root resulting in cardiac tamponade and prolonged resuscitation and one patient died due to multi-organ-failure in the setting of ATAAD with consecutive open-chest-treatment because of hemodynamic instability and bleeding. Four patients (3%) suffered from perioperative stroke, 5 patients (4%) required the implantation of a permanent pacemaker. Ninety-seven percent of the patients were discharged from hospital with aortic regurgitation ≤II. The mean AV-gradient at discharge was 8 ± 4 mmHg. Intraoperative and discharge data are presented in Tables 2, 3.

Long-term outcomes

The completeness of follow-up was 99%. Only one patient was lost to follow-up due to moving abroad. Median follow-up-time was 8.7 years (6.2–12.9). Eighteen patients (14%) died during the follow-up, 15 patients (12%) had to be re-operated due to valve or graft-related complications at a median of 10.7 years (6.1–15.6) after initial David operation. Reasons for reoperation were: aortic regurgitation (6 patients, 40%), aortic stenosis (7 patients, 47%) and aortic valve endocarditis (2 patients, 13%). Of the 15 patients that needed reoperation/reintervention, 7 (47%) received a TAVI, 8 (53%) patients underwent redo-surgery including aortic valve replacement. Median age at reintervention/reoperation was 73.8 years (64.2–79.4) and 46.6 years (27.7–60.3) respectively. There were no cases of perioperative mortality for both approaches.

TABLE 2 Intraoperative data.

CPB-time (min)	186 ± 73
Aortic cross-clamp time (min)	135 ± 48
Graftsize (mm)	28 ± 2
Plications performed	
Overall	39 (30%)
Noncoronary cusp	27 (21%)
Right coronary cusp	25 (19%)
Left coronary cusp	25 (19%)
Additional procedures	
+ ACBP	9 (7%)
+ Other Valve	5 (4%)
+ Hemiarch	11 (8%)
+ Arch	5 (4%)

TABLE 3 Discharge data.

In-hospital mortality	3 (2%)
Perioperative cerebrovascular event	4 (3%)
Perioperative pacemaker-implantation	5 (4%)
Echocardiography at discharge	
Aortic regurgitation	
None (0)	42 (33%)
Trivial (1)	59 (46%)
Mild (2)	22 (17%)
Moderate (3)	4 (3%)
Severe (4)	0 (0%)
LVEF (%)	57 ± 8
LV-Diameter	
LVESD (mm)	35 ± 8
LVEDD (mm)	52 ± 7
Aortic valve gradient	
dPmax (mmHg)	16 ± 8
dPmean (mmHg)	8 ± 4
Aortic diameters	
Annulus (mm)	23 ± 2
Aortic root (mm)	33 ± 4
Ascending aorta (mm)	31 ± 4

A Kaplan-Meier analysis showing reoperation-free survival-rates is provided in Figure 1. Reoperation-free survival at 1, 5, 10, and 15 years was 97.7% ± 1.3%, 93.5% ± 2.4%, 87.0% ± 3.5%, and 66.6% ± 6.5%, respectively. Log-rank-test revealed no difference in reoperation free survival between AVSRR in bicuspid vs. tricuspid valve ($p = 0.55$, Figure 2) or AVSRR in case of preoperative aortic regurgitation ≥3 vs. <3 ($p = 0.29$, Figure 3). However, reoperation free survival was significantly longer in patients without left ventricular dilatation [left ventricular end diastolic diameter (LVEDD) <55 mm vs. LVEDD ≥ 55 mm] at the time of AVSRR [log-rank-test $p = 0.033$/Cox-regression model $p = 0.027$, HR 3.583 (1.152–11.143), Figure 4].

At latest follow-up, 100 patients were alive and did not require a re-operation. Clinical and echocardiography-data were obtained from all of them (100%). Median follow-up time for this patient-group was 8.2 years (6.1–12.2) for the clinical assessment and 7.2 years (4.3–10.7) for the echocardiography-data. In follow-up, 98% of the patients were in functional NYHA Class I or II. Eight years after surgery 91% of the patients remained with aortic regurgitation ≤2 (Figure 5). Left ventricular ejection fraction and diameters at the level of the aortic annulus, the sinus of Valsalva, the ascending aorta as well as left ventricular end diastolic diameter remained stable over the years. Clinical and echocardiographic follow-up data are summarized in Table 4.

Discussion

Aortic valve sparing root replacement is considered the optimal treatment option for significant aortic root dilatation in case of suitable valve anatomy, especially in young patients. When performed in experienced centers with a well-structured AVSRR program, excellent results can be expected in adolescents as well as younger adults with reoperation-free survival rates above 70% in 5 to 15-year follow-up (10–13). In this study, we demonstrated, that comparable results can be obtained in a teaching-center as well, where AVSRR-surgeries are performed by way more different surgeons than in specialized centers. The results achieved in our institution do not diverge much from results in clinics with highest expertise in AVSRR.

AVSRR using the David technique is a demanding operation, usually performed by experienced surgeons. As in every other, technically demanding procedure, it is known that the surgeon's experience has a direct impact on early- and long-term outcomes of AVSRR procedures (14). Still it is noteworthy, that not only the surgeons experience is crucial to achieve best possible results. Critical patient selection with precise preoperative assessment of the aortic root as well as close aftercare of the patients, especially in case of a dilated left ventricle (15), is mandatory for procedural and long-term success.

Twenty four percent of the patients in this study had an underlying CTD, a substantial proportion (26%) presented

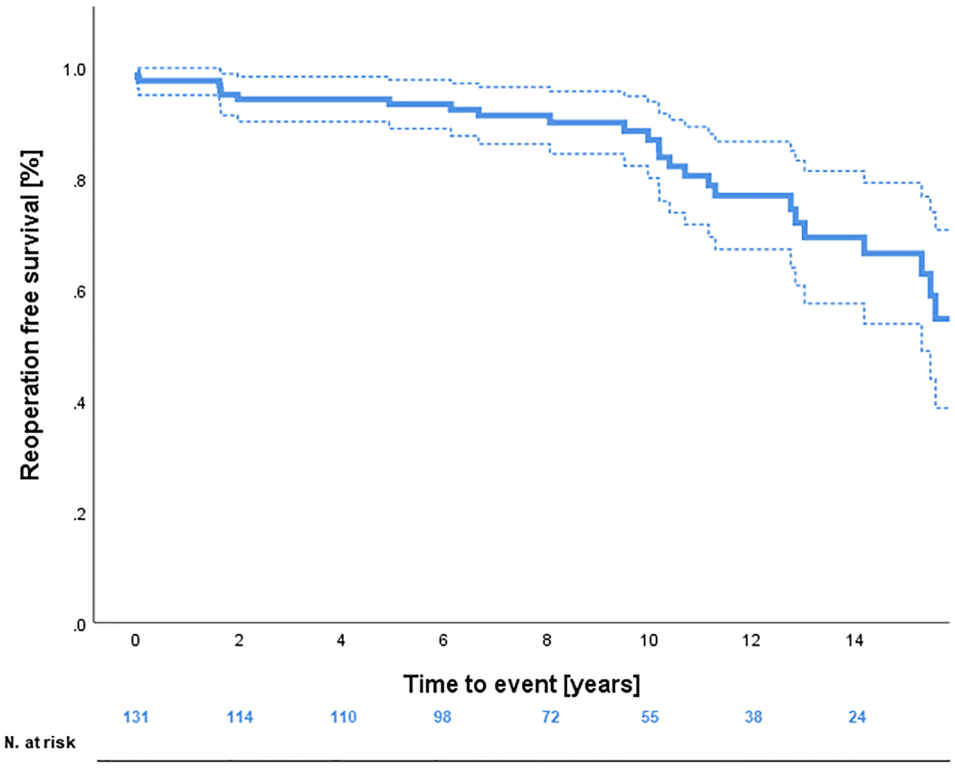

FIGURE 1
Reoperation free survival after AVSRR with 95% confidence-interval.

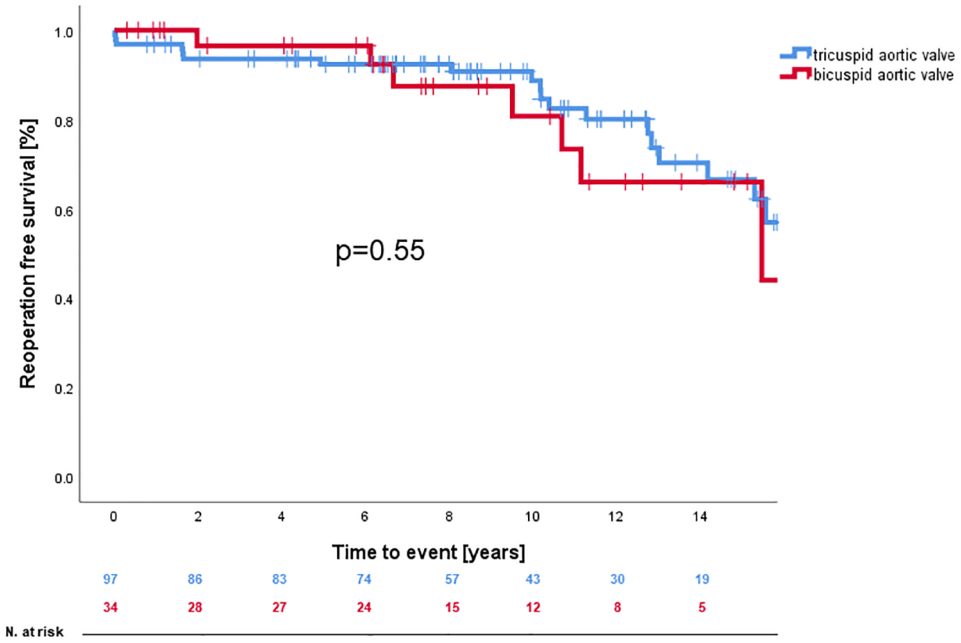

FIGURE 2
Reoperation free survival after AVSRR with bicuspid vs. tricuspid valve.

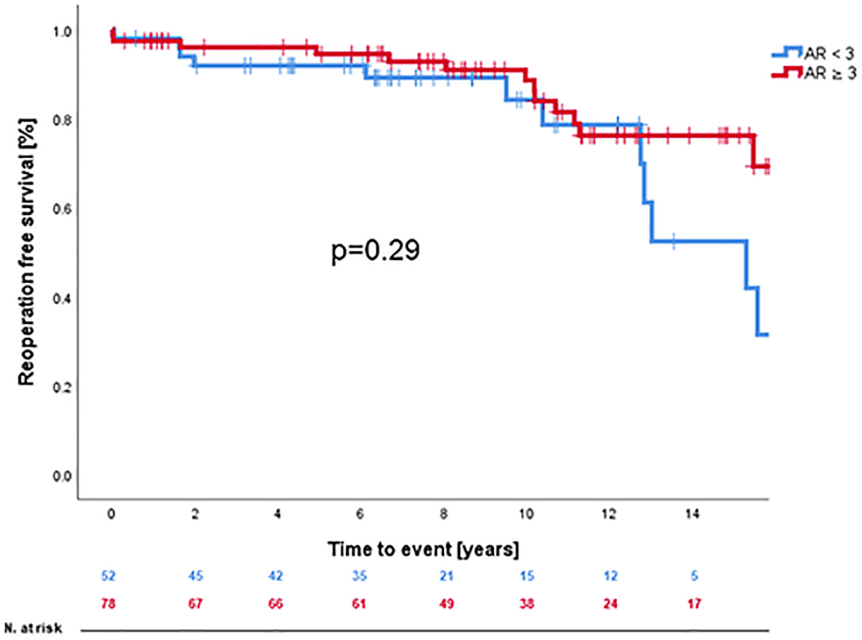

FIGURE 3
Reoperation free survival after AVSRR with aortic regurgitation ≥3 vs. <3.

with a bicuspid valve and 21% of the cases were performed under aggravating circumstances such as reoperative heart surgery or in the setting of an ATAAD. Although good long-term-results can be achieved with AVSRR in emergency surgery for aortic root-related diseases, AVSRR poses an increased risk for additional complications and poor long-term-outcomes when performed in this condition (16). This is especially relevant in case of unsatisfactory root reconstruction when the aortic root eventually has to be replaced by a composite valve graft in a second cardiopulmonary-bypass run. This study does not include an intention-to-treat analysis and therefore the question,

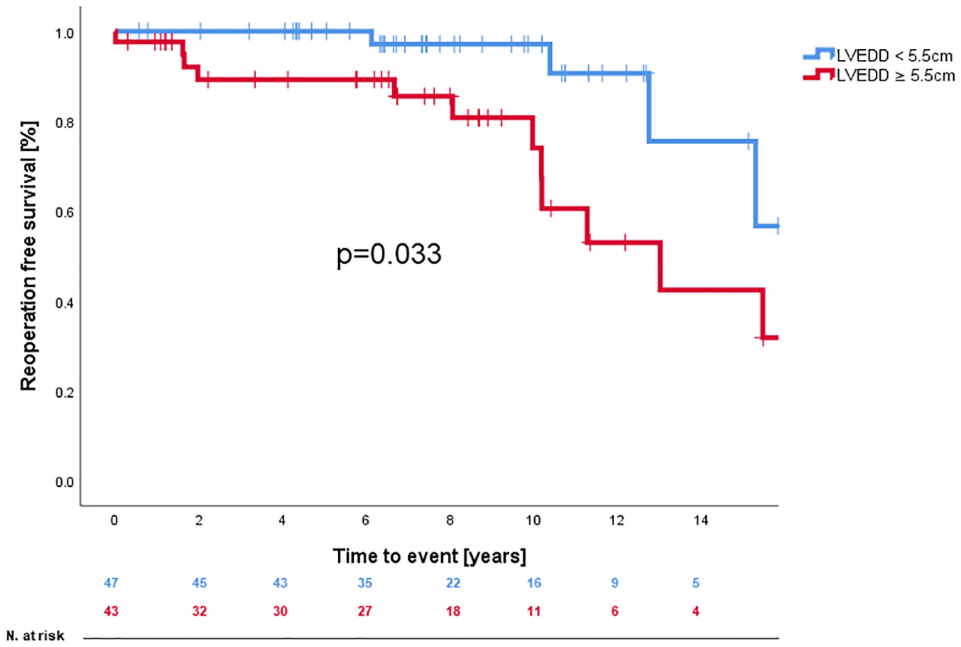

FIGURE 4
Reoperation free survival after AVSRR with LVEDD <5.5 vs. ≥5.5 cm.

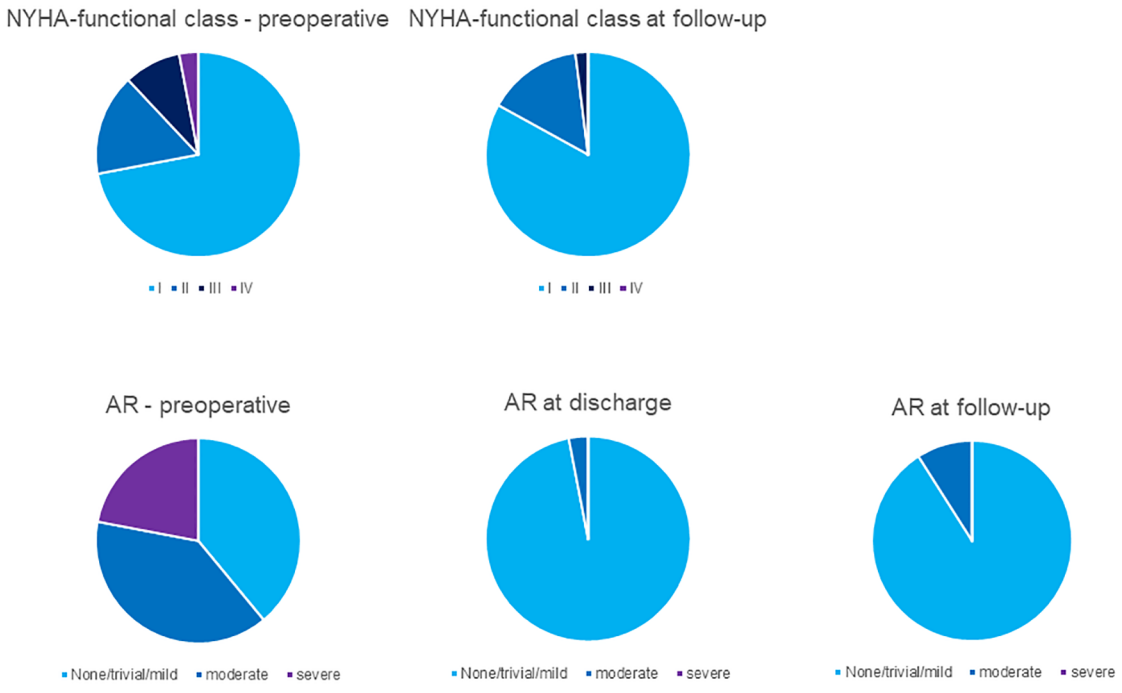

FIGURE 5
NYHA functional class and aortic regurgitation preoperative, postoperative and in late follow-up.

if AVSRR should be considered in these kinds of extraordinary settings cannot be answered.

In our study, reoperation-free long-term survival was significantly lower once left ventricular end diastolic diameter exceeded 55 mm. This indicates, that decision on operative timing in non-ATAAD should not only be based on symptoms or degree of aortic regurgitation, but also on left ventricular dilatation as it is stated in the current european guidelines for the management of valvular heart disease (17).

TABLE 4 Follow-up data.

Clinical follow-up ($n = 130$)	
Duration clinical follow-up (years)	8.7 (6.2–12.9)
Status at follow-up	
Alive	100 (76%)
Dead	18 (14%)
Reoperated	15 (12%)
Reoperated and dead	2 (1%)
Postoperative cerebrovascular event	4 (4%)
Clinical follow-up—alive and not reoperated ($n = 100$)	
Duration clinical follow-up (years)	
NYHA Functional class	8.2 (6.1–12.2)
NYHA I	83 (83%)
NYHA II	15 (15%)
NYHA III	2 (2%)
NYHA IV	0 (0%)
TTE follow-up—alive and not reoperated ($n = 100$)	
Duration TTE follow-up (years)	7.2 (4.3–10.7)
Aortic regurgitation	
None (0)	19 (19%)
Trivial (1)	35 (35%)
Mild (2)	37 (37%)
Moderate (3)	9 (9%)
Severe (4)	0 (0%)
LVEF (%)	61 ± 6
LV-Diameter	
LVESD (mm)	33 ± 7
LVEDD (mm)	51 ± 7
Aortic valve gradient	
dPmax (mmHg)	13 ± 10
dPmean (mmHg)	8 ± 7
Aortic diameters	
Annulus (mm)	24 ± 3
Aortic root (mm)	34 ± 4
Ascending aorta (mm)	32 ± 4

The main expected advantages of a valve sparing procedure are the lower risk of infective endocarditis compared to prosthetic valve replacement and no need for long-term anticoagulation as required after implantation of mechanical prostheses. This finding made AVSRR surgery an attractive treatment option for younger patients, especially when it can be expected that the re-implanted valve may last longer than a biological prosthesis. However, 15% of the patients treated with the David operation had to be re-operated during follow-up, mostly due to valve related complications thus underscoring the need for careful patient selection and surveillance during follow-up. Relapse of significant aortic regurgitation was observed almost as frequent as the development of aortic stenosis. Reoperation for valve-related problems is feasible, however associated with an increased surgical risk due to mediastinal scaring and adhesions. For this reason, in this study, almost half of the patients that needed reoperation/reintervention due to valvular problems, were selected for transcatheter valve implantation (18).

Despite technical challenges especially in asymmetrical commissural orientation (19), both bicuspid as well as tricuspid valves can be re-implanted with very good results. A precise assessment of the aortic root geometry is crucial to successful treatment (20). Minor corrections on the free edge of the leaflets can be performed using central suture plications at the *nodulus Arantii*, a technique overall used in 30% of the patients undergoing AVSRR in this study (32% in tricuspid valves, 24% in bicuspid valves). No differences in reoperation-free long-term survival were observed comparing patients that were treated with leaflet-plications to those without correction of leaflet-prolapse.

Strengths and limitations

The strength of this study is in the 99% completeness of follow-up at our clinic or referring physicians. Knowing that the possible onset of aortic valve deterioration or significant AV regurgitation need close monitoring, patients after AVSRR are checked for AV-dysfunction or left ventricular dilatation on a yearly basis.

This study has some limitations, foremost the retrospective study design and the long study period in which perioperative care, perfusion techniques etc. might have changed over time. Group-heterogeneity may confound definitive conclusions. Despite data collection for this study was carefully done by one person applying the exact criteria outlined in the methods-section, echocardiography-data were assessed by different cardiologists following different protocols and may therefore contribute to selection bias. The operations analyzed in this study were performed by a total of 17 different surgeons over a long period of time. Individual experience as well as individual treatment concepts may also have a direct impact on patient-outcomes. However, the low inclusion rate and heterogeneity in the indications, procedures and results of this study may actually represent the outcomes of AVSRR in low volume centers and directly support the feasibility of the procedure even if it's actually performed under training-conditions by different surgeons.

Additionally it needs to be underlined, that only a limited number of patients reached long-term follow-up >10 years. Especially in the context of alternative replacement of the aortic valve with a bio-prosthesis, which nowadays is expected to last longer than 10 years, conclusions weather AVSRR is superior in long-term follow-up need to be critically evaluated.

Conclusion

Despite being a technically demanding procedure, AVSRR using the David operation can be performed safely in mid-volume centers with excellent perioperative and 10-year follow-up outcomes. The results presented in this study may justify the use of AVSRR-surgery in well evaluated younger patients in centers where only a handful of cases are performed yearly. However, being a time-consuming procedure, dependent on preoperative planning, David operations should preferably be perfomed in elective settings or remain in experienced hands, under aggravating circumstances such as redo-heart-surgery or ATAAD.

In 10 year-follow-up we experienced few root related complications and the majority of the patients remained asymptomatic with stable root diameters and non-significant aortic regurgitation over time. Aortic valve sparing procedures offer a safe alternative for complete root replacement especially in younger patients in whom the intake of oral anticoagulation is undesirable.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving human participants were reviewed and approved by Kantonale Ethik-Kommission Zürich. The ethics committee waived the requirement of written informed consent for participation.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

The original contributions presented in the study are included in the article/supplementary materials, further inquiries can be directed to the corresponding author/s.

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Case report: Video-assisted minimally invasive mitral and pulmonary valve replacement as reoperation in patient with situs inversus totalis

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Dextrocardia with situs inversus totalis is a rare congenital condition. We report herein a first experience of video-assisted minimally invasive mitral and pulmonary valve replacement through right anterior mini-thoracotomy as reoperation in patient with this complex anomaly. The good clinical and cosmetic results demonstrate that this innovative technique can be safely performed even in difficult anatomical conditions.

KEYWORDS

minimally invasive surgery, dextrocardia situs inversus totalis, mitral valve, pulmonary valve, reoperation

Case description

A 50-year-old man diagnosed with dextrocardia and situs inversus totalis (DSIT) was referred at our institution with symptoms of exertional dyspnea due to severe mitral and pulmonary valve regurgitation for surgical replacement of both valves (**Figure 1A**). A previous surgical closure of an atrial septal defect was performed through conventional sternotomy 30 years ago. Preoperative computed tomography angiography (CTA) of the chest and abdomen as well as a transthoracic echocardiography (TTE) confirmed the DSIT, citing a light rightward rotation of the apex around the central axis, and showed a very complex anatomy of the heart (**Figure 1B**). The left atrium (LA) and left ventricle (LV) were placed on the right side, the right atrium (RA) and the right ventricle (RV) on the left side, with the apex lying behind the sternum (**Figure 1C**). CTA also showed the aorta situated anterior and to right of the main pulmonary artery, with the anatomical right pulmonary artery passing under the aortic arch, suggestive of an anatomically corrected malposition of the great arteries with the I-L-D type (1).

Surgical technique

After induction of general anesthesia, right vasa femoralis was cannulated through 2 cm skin incision. Cardiopulmonary bypass (CPB) was started. Right anterior mini-thoracotomy through 5 cm skin incision at the fourth right intercostal space (ICS) was performed (**Figure 2A**). Intercostal tissue has been divided and a soft tissue retractor (Valve Gate™

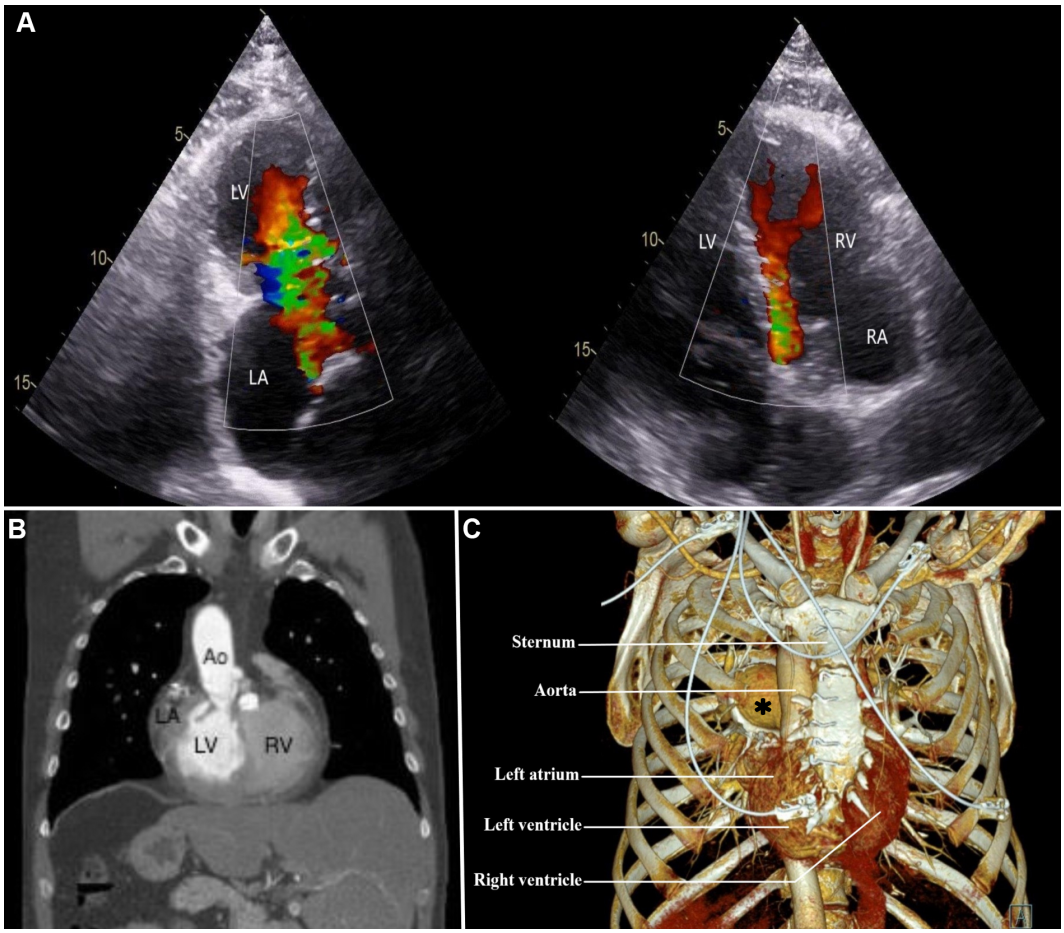

FIGURE 1
(A) preoperative transesophageal echocardiography showing mitral and pulmonary valve regurgitation; (B) computed tomography angiography of the chest and upper abdomen, demonstrating a rightward orientation of the left atrium, and liver at the left side; (C) computed tomography angiography with 3D reconstruction of the chest, illustrating a right-sided location of the left atrium and ventricle from the sternum. Ao, aorta; LA, left atrium; LV, left ventricle; RA, right atrium; RV, right ventricle. Asterisk, right pulmonary artery.

Soft Tissue Protector, Geister, Germany) has been placed followed by dissection of adhesions until 2 cm above the phrenic nerve to open the pericardium transversely. After exposure of ascending aorta, 2 small incisions for aortic clamp and 3D camera port (Aesculap Einstein Vision, Tuttlingen, Germany) were placed in the third ICS. Cardioplegia catheter (Medtronic DLP 9F, Ref 10012) was inserted into the ascending aorta. The aorta was cross-clamped with Chitwood clamp and crystalloid cardioplegia was administered in an antegrade fashion. Mitral valve (MV) was exposed after dissecting of Waterston's groove, opening the LA and retracting the anterior LA and septum anteriorly using a retractor (Valve Gate™ Mini-Thoracotomy Retractor, Geister, Germany). The anterior leaflet was totally resected. After annulus sizing, annular sutures were placed and a 29 mm mechanical valve prosthesis (ATS Medical, Inc, Minneapolis, MN) was implanted using automatic fastener technology (Cor-Knot®, LSI Solutions, USA). After closing the LA, pulmonary valve (PV) was exposed through transverse incision of the right pulmonary artery (rPA). After resection of the leaflets and regular decalcification, a sutureless self-expanding biological valve prosthesis size S (Perceval S, Sorin, Saluggia, Italy) was retrogradely implanted, followed by closure of the rPA.

After de-airing the heart, the aorta was declamped and the patient was weaned from CPB after placement of a left ventricular pacing wire. The femoral decannulation was followed by closure of the femoral artery and vein and layered closure of the right groin. A drain trough the cross-clamp incision was placed and the ribs are secured with two FiberWire (Arthrex; Naples, FL, USA). Wounds were then closed in layers. Intraoperative echocardiography showed competent implanted prostheses in the mitral and pulmonary positions.

CPB time and cross clamp time was 108 min and 65 min respectively. Our patient had an uneventful recovery after the surgery. He was extubated on the 1st postoperative day and transferred out of the intensive care unit on the second post-operative day. On the regular station he was ambulated early with good results. On the 4th post-operative day, an elevation of his inflammatory markers entailed the start of empirical anti-biotherapy, which normalized shortly thereafter. The patient was started on oral anticoagulation therapy

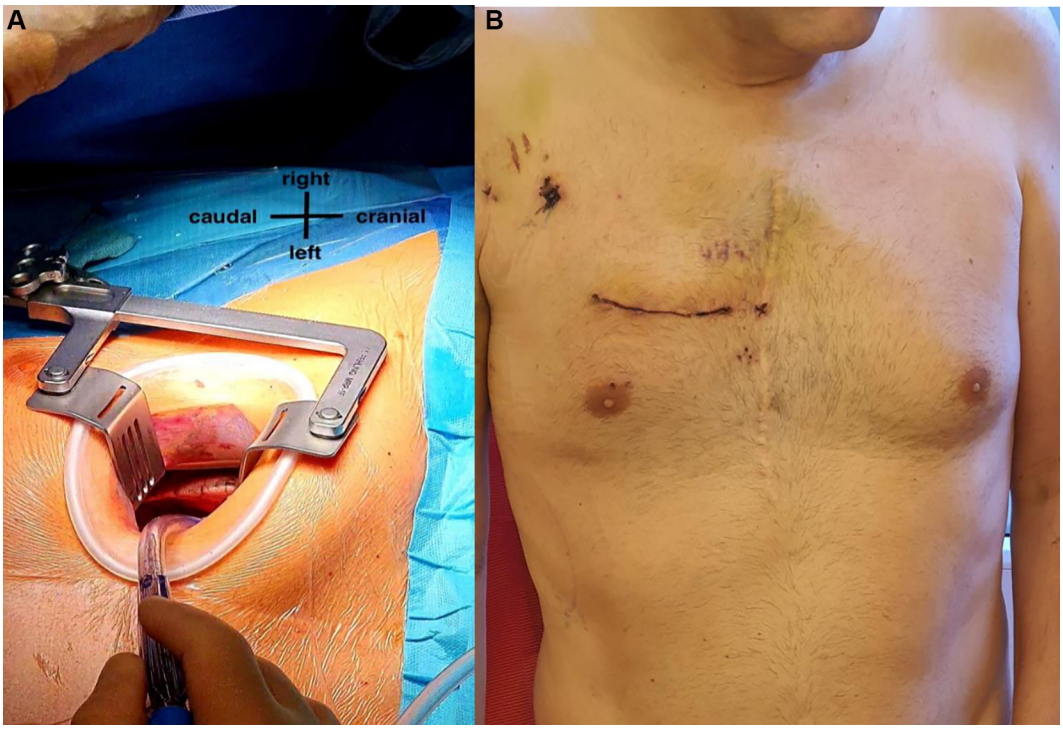

FIGURE 2
(A) right anterior mini-thoracotomy through a 5 cm skin incision at the fourth right intercostal space. (B) The patient at 6th postoperative day with the minimal incision right.

(Marcumar®) for the mechanical valve. He was discharged home on the 10th postoperative day (**Figure 2B**). Two days following his discharge, a control TTE was done showing a normal left ventricular ejection fraction and competent pulmonary and mitral valves.

A one-year follow-up revealed that the patient was doing well, with a NYHA I-II classification of dyspnea, and had undergone a cryoablation procedure for atrial fibrillation by his cardiologist. His follow-up TTE also revealed a good left ventricular ejection fraction and good prosthetic valve functions, as well as no paravalvular leak. The patient reported otherwise excellent cosmetic results, and no other pertinent symptomatic changes or clinical findings.

Discussion

Video assisted minimally invasive approach through RAMT for combined MV and PV surgery as a reoperation represents a considerable technically surgical challenge for cardiac surgeons especially when achieved in a DSIT patient, which is a congenital anomaly with an incidence of 1/10.000 births (2). Due to the complexity of the anatomy in patients with DSIT, the most common access for cardiac surgeries remains the conventional median sternotomy (3, 4). It is a safe and feasible procedure that is associated with good long term outcomes, and allows for the surgical management of a wide spectrum of cardiac diseases with a multitude of anatomical variations, including concomitant cardiac pathologies (5). It is however a considerably invasive approach associated with substantial trauma to the chest wall and intrathoracic structures, and repeat sternotomy is itself associated with early mortality, particularly for adult patients with congenital heart diseases (6).

In contrast, minimally invasive approaches to valvular surgery (MIVS) have already been shown to offer several advantages over classical sternotomy, including a better pain profile, less requirements for blood transfusion, shorter intensive care stay and satisfactory cosmetic results by sparing the surgical trauma of the classical approach (7, 8).

The current literature does not include reports of minimally invasive approaches to valve replacements in patients with situs inversus associated with levocardia and lacks considerably with regards to DSIT, some reports however describe a minimally invasive replacement of isolated aortic valve in patients with DSIT via a left sided access (3, 9).

In patients with situs solitus–normal anatomy, minimally invasive concomitant pulmonary and mitral valve replacement surgery through mini-thoracotomy can be performed from a left-sided approach since the left anterior mini-thoracotomy (LAMT) provides excellent access to the pulmonary valve and right ventricular outflow tract (10).

In DSIT however the anatomy is mirror inverted, which makes a right-sided approach appropriate in order to access the required heart structures providing a good exposure of both the interatrial groove and the right pulmonary arterial tree. Situs inversus can nonetheless be associated with additional anatomical variations

and anomalies such as azygos continuation of the inferior vena cava, anomalous pulmonary venous return, or malposition of the great arteries (11). In addition to the challenges of video-assisted minimally invasive concomitant valve surgery as reoperation such as the limited field of view and the steep learning curve, and the adhesions resulting from a previous cardiac surgery by sternotomy, this presents an additional technical burden in the treatment of such pathologies such as in our case, and makes extensive pre-operative investigations and thorough imaging crucial and necessary in order to correctly identify the anatomy of each patient and accordingly plan the best surgical approach.

To the best of our knowledge, we report a first case combining these pathologies and abnormalities with video-assisted minimally invasive concomitant PV and MV surgery from a right sided access. The success in this case was the meticulous preoperative diagnostic evaluation, the recognition of anatomical abnormalities, use of 3D camera and the sutureless self-expanding biological valve prosthesis in the PV offering the patient all the benefits of MIVS.

We accomplished the surgery without particular difficulties and with very acceptable CPB and cross clamp time. One-year Follow-up revealed excellent echocardiographic, cosmetic, and clinical outcomes.

Conclusion

Video-assisted minimally invasive double valve surgery trough RAMT in a patient with DSIT as reoperation was performed safely with good clinical and cosmetic results.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by ethics committee of the Medical Association of North Rhine in Germany (Ifd. Nr.: 82/2021). The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

FB, SSi, and AE contributed to conception and design of the study. SSa organized the database. SSa wrote the first draft of the manuscript. AB contributed to video editing. AB, and AE wrote sections of the manuscript. All authors contributed to the article and approved the submitted version.

Conflict of interest

FB discloses speakers' honoraria and/or consulting fees from Edwards Lifesciences, LIS and Abbott.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fcvm.2023.1053923/full#supplementary-material

SUPPLEMENTARY VIDEO S1
Video showing step by step the progress of the operation.

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Right anterior mini thoracotomy for redo cardiac surgery: case series from North America and Europe

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Background: Right anterior mini thoracotomy (RAMT) for aortic valve replacement (AVR) is a minimally invasive procedure that avoids sternotomy. Herein, we report the outcomes of patients who underwent redo-cardiac via a RAMT approach for AVR.

Methods: This case series reports the clinical outcomes of 14 consecutive redo operations, done in Calgary (Canada) and Gdansk (Poland) between 2020 and 2023. Primary outcomes were 30-day mortality and disabling stroke. Secondary outcomes included surgical times, hemodynamics, permanent pacemaker implantation (PPM), length of ICU and hospital stay, new post-operative atrial fibrillation (POAF), post-operative blood transfusion, incidence of acute respiratory distress syndrome (ARDS), rate of continuous renal replacement therapy (CRRT) and/or dialysis, and chest tube output in the first 12-hours after surgery.

Results: Nine patients were male, and the mean age was 64.36 years. There were no deaths, while one patient had a disabling stroke postoperatively. Mean cardiopulmonary bypass and cross clamp-times were 136 min and 90 min, respectively. Three patients needed a PPM, 3 patients needed blood transfusions, and 2 developed new onset POAF. Median lengths of ICU and hospital stays were 2 and 12 days, respectively. There was no incidence of paravalvular leak greater than trace and the average transvalvular mean gradient was 12.23 mmHg.

Conclusion: The number of patients requiring redo-AVR is increasing. Redo-sternotomy may not be feasible for many patients. This study suggests that the RAMT approach is a safe alternative to redo-sternotomy for patients that require an AVR.

KEYWORDS

right anterior mini thoracotomy, aortic valve replacement, redo-surgery, minimally-invasive valve surgery, minimally-invasive surgery

Introduction

Aortic valve replacement (AVR) is the gold standard treatment for severe, symptomatic aortic valve stenosis (AS). Despite an aging population, surgical and transcatheter advances have facilitated repeat interventions on dysfunctional native and prosthetic aortic valves. When considering re-intervening on a diseased prosthetic aortic valve, options include redo-surgical aortic valve replacement (SAVR) or valve-in-valve (ViV) transcatheter aortic valve replacement (TAVR). Several studies over the past 10 years have demonstrated favourable outcomes with each of these strategies (1–5). Generally, it is believed TAVR offers a minimally-invasive low risk procedure, but with limited durability, whereas redo-SAVR is associated with higher risk, but greater durability. Redo-SAVR via RAMT may represent a compromise, offering a less invasive option with greater durability.

Conventional SAVR is performed via full median sternotomy, while minimally-invasive SAVR can be done through either a hemi-sternotomy or a right anterior mini thoracotomy (RAMT). Although the current literature on redo-SAVR is mainly focused on redo-full median sternotomy or hemi-sternotomy approaches, there is a paucity of data reporting the clinical outcomes of redo-AVR, performed through a RAMT incision. When compared to conventional SAVR, RAMT has been shown to have similar clinical outcomes, less pain, and less blood transfusions (6–10). There is also evidence showing that patients undergoing RAMT can have an expedited return to their functional baseline secondary to quicker mobilization, better pain control, and no sternal precautions (11). RAMT access is well-liked by patients, as many associate full median sternotomy with increased morbidity and prolonged rehabilitation time. For these reasons, in the appropriate patient, RAMT is our preferred approach for redo-AVR.

Herein, we present the clinical outcomes of redo-AVR, performed via RAMT (redo-RAMT AVR) at two centers in North America and Europe. We show that a redo-AVR can be safely performed in appropriately selected patients through a RAMT approach. Our study provides original, real-world data on redo-RAMT AVR from two vastly different regions.

Patients and methods

Patient cohort

This case series involved retrospective collection of data to review the clinical outcomes of patients undergoing redo-RAMT AVR at a Canadian and a Polish center. All redo-operations were performed by 3 surgeons, who routinely perform minimally invasive valve surgery, between June 2020 and August 2023. This study was approved by the Conjoint Health Research Ethics Board at the University of Calgary and the Medical University of Gdansk underlying the Declaration of Helsinki (Ethics IDs: REB18-0042 and 062/2022, respectively).

Study endpoints

Primary outcomes were death secondary to cardiac cause within 30-days of surgery and disabling post-operative stroke. Secondary outcomes included surgical times, permanent pacemaker implantation (PPM), length of intensive care unit (ICU) stay, length of hospital stay, new post-operative atrial fibrillation (POAF), post-operative blood transfusion, incidence of acute respiratory distress syndrome (ARDS), rate of continuous renal replacement therapy (CRRT) and/or dialysis, and chest tube output in the first 12-hours after surgery. Echocardiographic parameters indicating correct valve implantation was assessed, including incidence of paravalvular leak and residual mean transvalvular gradient.

Preoperative and intraoperative considerations

Perioperative considerations for RAMT AVR have been described in detail previously (12). The same considerations are generally applicable for redo-operations through a RAMT incision (Figure 1) and are indicated for an AVR. Briefly, the ideal candidate will not have an elevated body mass index, their

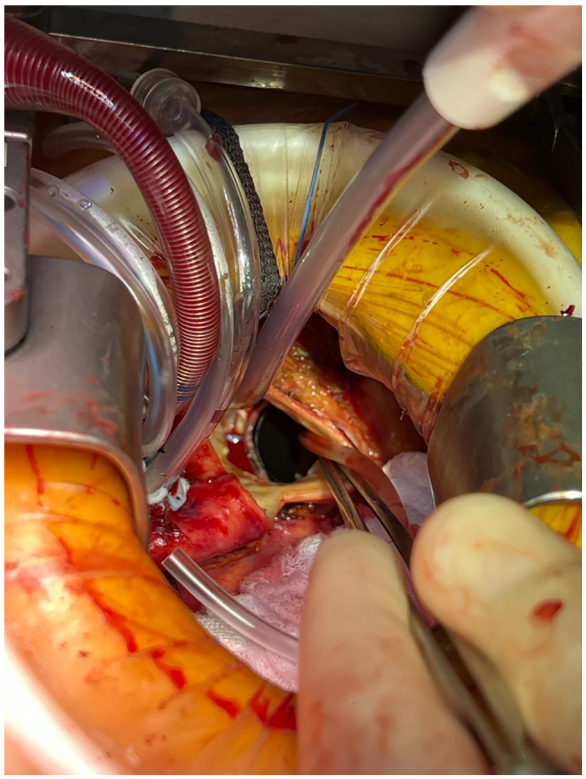

FIGURE 1
Redo-RAMT for a patient with a mechanical prosthetic aortic valve in-situ who presented with valve thrombosis. The mechanical valve was replaced with a bioprosthetic valve through a RAMT incision.

aorta will not be shifted left-ward, the distance from the aortic valve to the incision is less than 9 cm, and the peripheral vessels are suitable for instituting CPB. While the authors of this study believe that a RAMT incision will provide similar exposure to the aortic valve irrespective of first-time vs. redo-surgery, since this is a complex operation, surgeons should be selective early in their experience. While no particular steps are taken in redo- vs. first-time RAMT, an important factor in selecting patients for a potential redo-RAMT AVR is the index cardiac operation. It is essential to be prepared when encountering a hostile intra-thoracic cavity with a RAMT approach as exposure, dissection, and access to the aortic valve may all be affected by dense pericardial adhesions. It may also be unsafe or unfeasible to remove a prosthetic aortic valve through a RAMT incision. In such situations, conversion to a sternotomy would be recommended.

Inclusion and exclusion criteria

In this case series, patients were considered as possible candidates for redo-surgery via a RAMT approach if they met the anatomical requirements noted before (12). If the risk of redo-sternotomy was deemed to be too high on preoperative imaging, a stronger consideration was given for a RAMT. Furthermore, this cohort of patients were determined to have a quicker return to their functional baseline, and voiced a preference to avoid a sternotomy if it did not place them at a higher surgical risk. Patients with active infective endocarditis, previous bypass grafts, and those requiring concomitant procedures were not considered for a RAMT incision. A CT chest, abdomen, and pelvis with contrast run-off was obtained for this cohort of patients. There were no patients with missing data, so all 14 consecutive patients were included in the cohort.

Results

Baseline patient demographics

Fourteen consecutive patients underwent redo-cardiac surgery for an AVR through a RAMT incision. Index operations were done through sternotomy ($n = 12$), mini-sternotomy ($n = 1$), and left thoracotomy ($n = 1$, for repair of coarctation of the aorta). Nine were male and the average age of the patient cohort was 64.36 ± 11.08 years. In the cohort, 9 patients had had a previous AVR; 1 had previously undergone mitral valve replacement (MVR), tricuspid valve replacement (TVR), and aortic valve repair; 1 had undergone MVR, tricuspid valve repair, and aortic valve repair; 1 had a mechanical MVR; 1 had undergone a left thoracotomy as a child to repair coarctation of the aorta; and 1 had undergone aortic valvulotomy. Finally, the mean European System for Cardiac Operative Risk Evaluation (EuroSCORE) II was 3.77% ± 3.54% for this case series. Patient demographics are listed in Table 1.

TABLE 1 Baseline patient demographics ($n = 14$).

Variable	
Age (y)	64.36 ± 11.08
Gender (male)	9
Hypertension	12
Dyslipidemia	6
Type II diabetes	5
Renal insufficiency	4
Peripheral arterial disease	1
Chronic obstructive lung disease	5
Cerebrovascular disease	2
Prior cerebrovascular event	3
Infective endocarditis	0
AF/flutter	4
Angina	9
CCS class I	6
CCS class II	3
Presyncope	1
Syncope (at least one episode)	1
Dyspnea	14
NYHA class I	0
NYHA class II	8
NYHA class III	3
NYHA class IV	3
Indication for surgery	
Aortic stenosis	14
Index operation	
AVR	9
MVR + TVR + AVr	1
MVR + TVr + AVr	1
MVR	1
Coarct repair	1
Valvulotomy	1
Index operation (approach)	
Full median sternotomy	12
Mini-sternotomy	1
Left thoracotomy	1
EuroSCORE II	3.77% ± 3.54%

Intraoperative details

Different types of valves were used in this case series. The type and size of the valves that were used is summarized in Table 2. A femoral cutdown was performed to establish peripheral CPB in all patients. The third rib was detached in 10 cases. There was no conversion to sternotomy and there were no concomitant procedures. The mean CPB and cross-clamp times were 137.69 ± 54.41 min and 90.47 ± 34.97 min, respectively. There was no incidence of paravalvular leak (PVL) greater than trace and the mean and peak transvalvular pressure gradients were 12.57 ± 5.94 mmHg and 25.69 ± 9.89 mmHg, respectively. Intraoperative details are summarized in Table 3.

Postoperative outcomes

There were no deaths at 30-days postoperatively, but 4 patients did have a neurological event postoperatively, with only 1 being

TABLE 2 Type of valve used.

Prosthetic	
Sorin perceval	3
Medium	2
Extra-large	1
Edwards intuity (23 mm)	1
Edwards magna ease	2
23 mm	1
25 mm	1
On-X	6
21 mm	4
23 mm	1
25 mm	1
Mosaic	2
21 mm	1
27 mm	1

TABLE 3 Intraoperative details.

Variable	
Conversion to median sternotomy	0
Rib detached at costo-chondral joint	10
Peripheral cardiopulmonary bypass (cutdown on groin vessels)	14 (14)
Use of intra-operative transesophageal echocardiography	14
Del nido cardioplegia	14
Cardiopulmonary bypass time (min)	137.69 ± 54.41
Cross-clamp time (min)	90.47 ± 34.97
Paravalvular leak	
Trace or trivial	1
Mild	0
Moderate	0
Severe	0
Average residual transvalvular pressure gradient (mmHg)	
Mean	12.57 ± 5.94
Peak	25.69 ± 9.89

disabling. The causes for the neurological events were hypoxic brain injury secondary to hypotension for 1 patient while they were undergoing continuous renal replacement therapy (CRRT); cortical laminar necrosis causing hypoxic brain injury in 1 patient; and self-limiting postoperative seizures in 2 patients. Three patients received blood products in the ICU: one patient was transfused 2 units of packed red blood cells (pRBCs), 1 patient received 4 units of pRBCs, and 1 patient received 1 unit of pRBCs. On the ward, 2 patients were transfused 2 units of pRBCs each. Three patients experienced new onset postoperative atrial fibrillation (POAF) after their operation and 3 required a permanent pacemaker (PPM). The average chest tube output in the first 12-hours after surgery was 271.43 ± 329.22 ml; of note, only one patient was taken back to the operating room emergently perioperatively for excessive bleeding. None of the patients had acute respiratory distress syndrome (ARDS). One of the patients required CRRT. Median length of ICU and hospital stays were 2 (IQR: 5) and 11 (IQR: 9) days, respectively. Postsurgical findings have been summarized in Table 4.

TABLE 4 Postoperative outcomes.

Variable	
Peri-operative mortality	0
Major disabling stroke with residual deficits	1
Emergency reoperation	1
Blood product transfusion in the ICU	
Packed red blood cells	7
Platelets	0
Average chest tube output in first 12-hours (mL)	271.43 ± 329.22 ml
Invasive ventilation (hours)	5.38 ± 2.85
Continuous renal replacement therapy	1
Hemodialysis	0
New onset atrial fibrillation	3
Permanent pacemaker	3
Dissection	0
Limb ischemia	0
Groin complications	0
Average length of stay (days)	
ICU	6.64
Hospital	14.93
Median length of stay (days)	
ICU	2
Hospital	11
Valve thrombosis	0
Valve infective endocarditis	0

Discussion

With an aging population, repeat interventions for cardiac diseases are becoming more frequent. In most cases, the index operation is performed through a full median sternotomy. Although preoperative planning (13) and identifying patients at risk of injury during re-entry can mitigate the risk of redo sternotomy (14), it is still associated with a higher rate of complications (15, 16). Results from the multicenter European RECORD (REdo Cardiac Operation Research Database) initiative showed that conventional redo sternotomy for AVR was associated with a hospital mortality of 5.1%, major re-entry cardiovascular complications at 4.9%, and stroke at 6.6% (17). The same study found that the risk of ARDS was 10.6%; acute kidney injury (AKI) was 19.3% (where the need for CRRT was 7.2%), the need for transfusions was 66.9%, and the PPM implantation rate was 12.7% (17).

With the growth of TAVR, repeat interventions on the aortic valve are more commonly done with a ViV transcatheter approach. While there are accumulating studies that compare first time and repeat transcatheter strategies to redo-SAVR (3, 18–21), a RAMT approach should offer an important alternative for these patients for several reasons. First, the long-term outcomes of transcatheter valves is not known; second, some patients may not be suitable candidates for transcatheter approaches and transcatheter valves; third, RAMT can facilitate excellent hemodynamic results with respect to PVL and trans-valvular pressure gradients; fourth, small prosthetic aortic valves may be excised and removed through a RAMT incision when the ViV TAVR option is not feasible; and fifth, RAMT can mitigate the risks associated with proper valve deployment during TAVR,

especially in patients with a prior mechanical mitral valve replacement (22).

The RAMT approach has been demonstrated to be safe for first time AVR in diverse patient populations, including octogenarians (23–26). A small number of studies have assessed the outcomes of minimally-invasive redo-AVR through hemi-sternotomy and RAMT (27–29). In a sub-population analysis of the Sutureless and Rapid-Deployment Aortic Valve Replacement International Registry (SURD-IR), Santarpino and colleagues focused on the sutureless and rapid deployment valves and reported the outcomes of 20 patients who underwent redo-RAMT AVR (27). In this registry study, among the redo-RAMT cohort, there were no deaths, while postoperative stroke rate was 4.8%, 3.6% of the patients required PPM, and bleeding requiring reoperation occurred in 8.9% of the patients (27). In a single-center study, Pindeda et al. compared the outcomes of redo-AVR via RAMT vs. median sternotomy (29). They found that in-hospital mortality was zero for the RAMT cohort vs. four (10%) in the median sternotomy group ($p = 0.08$), whereas postoperative complications occurred in six (17%) vs. 19 (46%) ($p = 0.005$) of these two groups, respectively. The median ICU and total hospital length of stay were 48-hours vs. 69-hours ($p = 0.03$), and 7-days vs. 9-days ($p = 0.03$) for the minimally-invasive and median sternotomy group, respectively (29). Although these are registry and single-center studies, respectively, they do support the safety of redo-AVR via RAMT.

The present study combines outcomes of redo-operations via a RAMT incision from a North American and a European center. We show that none of the patients died perioperatively and only one patient had a disabling stroke. Importantly, in our cohort the transfusion rate was lower that quoted in the European RECORD initiative (50% vs. 70%) (17). The same trend was noted for rate of ARDS, while similar rates were noted for CRRT in our study and the RECORD initiative. It is important to note that in this cohort, 6 of 14 patients received a mechanical prosthetic valve, highlighting the possibility of sewing in such a prosthetic through a RAMT incision in a patient with previous surgery. As expected, the transvalvular pressure gradients for these 6 patients was high, thus increasing the cohort's intraoperative valve hemodynamics. With respect to the neurological events observed in our cohort, while high (4/14 patients), their underlying cause cannot be fully attributed to intraoperative complications. Nevertheless, future studies should closely monitor and report the incidence, cause, and severity of any neurological events in patients undergoing this type of high-risk operation.

To further highlight the safety of employing a RAMT approach after prior cardiac surgery, the operations were performed by 3 different surgeons, suggesting that this strategy can be considered in carefully selected patients. These 3 surgeons routinely perform minimally invasive valve surgery, so were comfortable with a RAMT incision for redo-operations. With respect to RAMT as a first-time operation, both centers perform approximately 60 cases on an annual basis. While our cohort included patients with previous valvular operations and one patient with a previous coarct repair, none had a prior CABG surgery. Although there is a case report of a patient who underwent RAMT for redo-AVR after CABG with bilateral internal thoracic arteries (30), patent grafts can significantly increase the operative risk and these patients may be best served with a TAVR if indicated. The authors of this study believe that patent grafts and especially patent bilateral internal mammary artery grafts stand as a contraindication for redo-RAMT AVR. Nevertheless, it will be important to make note of any larger studies that report the outcomes of patients with prior CABG surgery who undergo a redo-operation through a RAMT incision. Finally, the authors would like to acknowledge that there may be concerns of encountering extensive right-sided pleural adhesions via RAMT. Surprisingly, however, very little adhesions are usually encountered through a RAMT incision even in patients whose right pleural space was opened or manipulated during their primary sternotomy.

Our study includes several limitations. First, the study size is small, which is reflective of RAMT being a relatively new approach for treating aortic valve disease. Second, the study does not report the long-term outcomes of the patient cohort. Third, the study lacks a comparator group, namely redo-sternotomy and/or redo hemi-sternotomy AVR. While comparing between surgical approaches is important, it is essential to have large sample sizes that can be propensity-matched to ensure appropriate analyses can be done when interpreting the results.

Conclusion

With an ageing population, patients requiring redo-cardiac surgery will continue to increase. In select patients where a redo-sternotomy is not safe or feasible, a RAMT incision may be considered. Although larger studies with longer follow-up period are needed, our study suggests that RAMT can yield similar clinical outcomes to a conventional redo-sternotomy in carefully selected patients.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by This study was approved by the Conjoint Health Research Ethics Board at the University of Calgary and the Medical University of Gdansk underlying the Declaration of Helsinki (Ethics IDs: REB18-0042 and 062/2022, respectively). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

AH: Conceptualization, Data curation, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. JF: Data curation, Writing – review & editing. MH: Data curation, Writing – review & editing. MK: Data curation, Writing – review & editing. MS: Writing – review & editing. DD: Writing – review & editing. CA: Writing – review & editing. WDK: Supervision, Writing – review & editing. WOK: Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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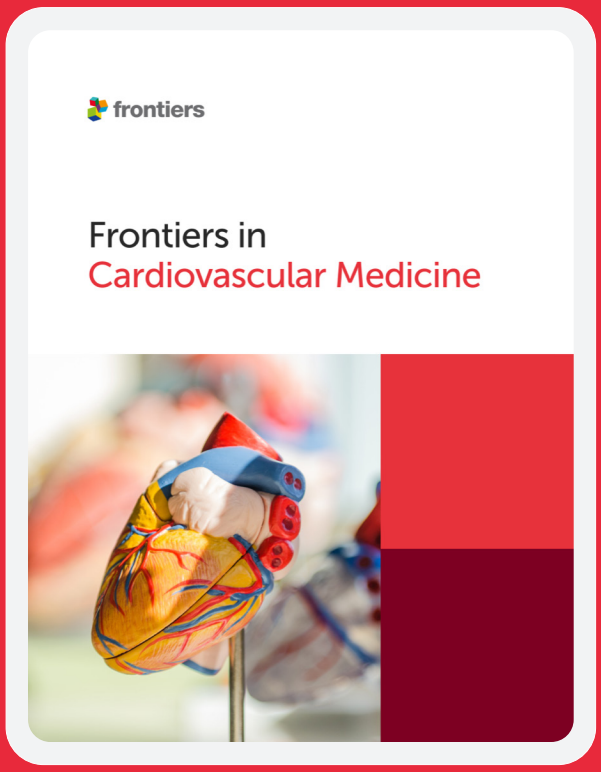

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