Minimally Invasive Cardiac Surgery

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Minimally invasive cardiac surgery (MICS) has gained a significant place due to the emergence of innovative tools and improvements in surgical techniques, offering comparable efficacy and safety to traditional surgical methods.

Keywords: cardiac surgery ; minimally invasive cardiac surgery ; innovative tools

1. Introduction

Over the last two decades, there has been a significant shift from traditional to minimal invasive cardiac surgery (MICS), driven by rapid technological advancements [1][2][3][4][5][6][7][8]. In 2021, Germany reported 36.8% of the performed aortic valve (AV) surgeries and 55.7% of all mitral valve (MV) surgeries to be in minimally invasive technique [9]. Moreover, an increase in the number of European institutions performing robotic cardiac surgery, growing from 13 in 2016 to 26 centers by 2019, has also been observed [4]. 75% of all cardiac surgeries are minimally invasive, and all staff surgeons are trained to perform the procedures. The growing adoption of MICS can be attributed to two primary factors. Firstly, it responds to the global imperative to combat cardiovascular diseases. Secondly, it is driven by acknowledging the myriad benefits of minimal access techniques in cardiac surgery [10]. These techniques encompass reduced surgical trauma, decreased postoperative pain, shorter hospitalization duration and costs, lower infection risk, faster recovery, quicker resumption of routine activities, and improved cosmetic outcomes [6][7][11][12][13][14][15][16]. MICS is defined by the Society of Thoracic Surgeons (STS) by two criteria: first, the use of smaller incisions and deviation from the conventional median sternotomy (MS), and second, performing surgery without cardiopulmonary bypass (CPB) [17][18]. The reduced invasiveness has been associated with reduced systemic inflammation, blood transfusion requirements, renal dysfunction, and vascular and neurological complications and shorter cross-clamp time [11][12][14][15][16][19][20][21][22][23][24]. Although MICS is technically more demanding and initial reports have demonstrated longer cross-clamp times in the MICS group, researchers have observed a decrease in cross-clamp timing, especially in minimally invasive mitral valve surgery (MIMVS), as shown by data published by the authors [25].

The field of cardiac surgery has been equipped with tools, such as video-assisted thoracoscopic and robotic technology, as well as advancements in perfusion techniques and transesophageal echocardiography, enabling the progression towards less invasive procedures.

2. Minimally Invasive Cardiac Surgery: Development and Current Standard

2.1. Minimally Invasive Coronary Revascularization

2.1.1. Coronary Artery Bypass Grafting (CABG)

After performing the first successful open-heart surgery on CPB in 1953, MS became the gold standard incision in cardiac surgery due to its safety, durability, and ease of reproducibility [26]. The landscape of conventional cardiac surgery began to change in 1967 with Kolesov’s groundbreaking procedure of performing coronary artery bypass grafting (CABG) on the beating heart via a left thoracotomy [27]. In the early 1990s, surgeons such as Benetti, Calafiore, Subramanian, and Boonstra conducted the first series of minimally invasive direct coronary artery bypasses (MIDCABs) in cases of left anterior descending artery (LAD) stenosis through a lateral thoracotomy [28][29][30][31]. They demonstrated the durability and safety of minimally invasive CABG in patients with LAD stenosis (0–3.8% in-hospital mortality, postoperative graft patency rate of 92% to 100%, 93% freedom from cardiac events in the first 30 days, and 92.2% after mean follow-up of 5.6 months) [28][29][30][31]. A significant challenge at the beginning of minimally invasive CABG surgery was accessing the coronary arteries and performing precise anastomoses through a minimal incision. Specialized retractors and stabilizers were developed to overcome the challenges faced during the surgical procedure. These improvements provided better visualization of the internal mammary arteries and the ascending aorta. A cardiac apical positioner was also implemented to manipulate the heart and enhance exposure to the coronary territories. Additionally, an epicardial stabilizer was used to stabilize the graft-to-coronary anastomosis. The anesthesiology team was vital in managing intrathoracic and intracardiac pressure to ensure optimal outcomes.

Technical advancements in the 1990s introduced port-access techniques, video-assisted thoracoscopic surgery (VATS), and non-robotic and robotic endoscopic coronary artery bypass grafting (TECAB) for graft harvesting and anastomosis in minimally invasive CABG [3][8][20][32]. In particular, robotic techniques for harvesting the left internal mammary artery (LIMA) with open graft anastomosis through lateral thoracotomy or completely robotic-performed surgery on a beating or arrested heart emerged as an option for performing CABG in a less invasive method [8][20][33]. While the initial application of TECAB focused on revascularizing left coronary vessels, it has been expanded to include total endoscopic harvesting of the right internal mammary artery (RIMA) and revascularization of the right coronary system [32]. Additionally, instances of TECAB using bilateral internal mammary arteries have yielded promising results [34].

MIDCAB under direct vision was the most common minimally invasive coronary revascularization method, with 46.9% of all analyzed minimally invasive CABGs [6]. Authors reported a 1.6% conversion rate to MS, 1.3% wound infections, and a 5-year survival rate of 91% in this group [6]. In their prospective two-center study of patients undergoing MIDCAB, McGinn et al. reported complete revascularization in 95% of cases, and the perioperative mortality rate stood at 1.3%, with a 3.8% rate of conversion to MS and 7.6% of patients requiring CPB [35]. The average hospital stay was six days [35]. During the mean follow-up of 19.2 ± 9.4 months, 3% of patients needed further percutaneous revascularization [35]. A case-matched study by Lapierre et al. demonstrated that MIDCAB patients had a statistically significant shorter median hospital stay (5 days vs. 6 days) and a faster median time to return to total physical activity (12 days vs. 36 days) compared to off-pump coronary artery bypass (OPCAB) [36]. In addition, Ziankou et al. indicated that patients undergoing minimally invasive CABG had shorter hospital stays (4.5 days vs. 7.5 days) and a decreased median time to resume complete activities by four times (14 days vs. 56 days) when compared to those undergoing CABG through MS [37].

Video-assisted CABG is a combination of thoracoscopic harvesting of the internal mammary artery (IMA) and direct coronary bypass grafting through a mini-thoracotomy without cardiopulmonary bypass is another method for minimally invasive coronary revascularization without cardiopulmonary [38]. Video-assisted CABG allows the harvesting of the IMA at full length and enables a direct lateral view of the graft rather than the divergent view that the surgeon faces in MIDCAB. The initial results by Benetti et al. demonstrated the absence of mortality and myocardial infarction (MI) and 0% morbidity during the hospital stay [38]. Antona et al. reported a 2.4% rate of acute MI and a 95.2% graft patency rate in the first month preoperatively. During the mean follow-up of 8.7 months, no deaths were registered, and there was no recurrence of angina pectoris symptoms [39]. The review of Bonatti et al. on video-assisted CABG reported a conversion rate to MS of 4.5%, a 1.4% rate of reoperation due to postoperative bleeding, a 0.4% rate of stroke, a postoperative dialysis rate of 1.3%, a wound infection rate of 1.7%, an in-hospital mortality rate of 0.8%, and a 92% survival rate at five years for the cases analyzed in [6].

TECAB with or without robotic assistance is the second (15.8%) and third (15.5%) frequent procedure for minimally invasive CABG, according to the analysis of Bonatti et al. for the last 25 years [6]. The literature review of Göbölös et al. on robotic TECAB for the past two decades reported conversion rates between 23.1% and 33% in the mid-2000s, which were significantly reduced below 10% in the last ten years [5]. The perioperative mortality rate reported was 0.8%, and there was a 2% incidence of surgical revisions required for postoperative bleeding [5]. Additionally, the incidence of stroke was 1.0%, acute renal failure occurred in 1.6% of cases, and in 13.3% of patients, new postoperative AF was documented [5]. The average duration of hospital stay was 5.8 days [5]. Even though TECAB is considered the most challenging among all minimally invasive CABG procedures due to its high technological requirements, from the standpoint of surgical invasiveness, it is the procedure that causes the most minor tissue damage [5][6]. The considerable investment in robotic equipment, the extensive training for surgeons and their teams, the heavy reliance on complex technology, and the critical interdependence of the surgical team members continue to be subjects of robust debate [6].

2.1.2. Hybrid Coronary Revascularization (HCR)

The combined guidelines from the American Cardiac Societies on percutaneous coronary intervention (PCI) and CABG define hybrid coronary revascularization (HCR) as a procedural strategy that combines the placement of a LIMA graft to the LAD artery with PCI on at least one additional non-LAD coronary artery [40]. Current guidelines from the European Society of Cardiology and the European Association for Cardio-Thoracic Surgery acknowledge HCR with a class IIb recommendation and changed the evidence level from C in 2014 to B in 2018, indicating that it may be considered for certain groups of patients. However, this is suggested to be performed in centers with ample experience in such procedures [41].

Multiple studies have confirmed the long-term higher survival rates and lower rate of major adverse cardiovascular events after CABG vs. PCI in patients with multivessel disease and for treatment of left main stem coronary artery disease, notably surpassing the percutaneous therapy with bare-metal or drug-eluted stents, primarily due to the better patency of the LIMA graft to the LAD [42][43][44][45][46].

Even though the advancements in minimally invasive surgery were reported to result in benefits such as quicker recovery, reduced hospital stays, and potentially fewer complications, surgical revascularization may pose challenges in fragile patients with concurrent health issues [47]. On the other hand, PCI revascularization typically carries a lower risk of immediate complications. Some studies have shown superior outcomes compared to saphenous vein grafts (SVGs) [48]. However, PCI has also been associated with increased intervention rates in patients with multivessel disease and coexisting conditions, such as diabetes mellitus [49][50].

Hybrid coronary revascularization might benefit this particular group of patients by combining the strengths of both methods: minimally invasive surgical revascularization of the LAD and PCI for non-LAD lesions [51]. These procedures are usually staged but may be performed within one treatment session. Extensive research has been conducted over the past decade to evaluate the procedural efficacy, short-term safety, and performance of HCR. The interim results showcased in the review by Moreno and DeRose indicate a graft patency rate for the LIMA-LAD bypass ranging between 93% and 100%, along with a survival rate of 93% after five years [52][53].

The concept of the HCR relies on the possibility of providing a personalized approach to coronary revascularization by combining the minimally invasive techniques of LIMA-LAD anastomosis with the targeted approach of PCI for non-LAD lesions. HCR offers the potential for improved outcomes and reduced risks, especially in high-risk patients [54][55]. However, it is essential to note that HCR is still relatively new compared to well-established conventional procedures, and there is a lack of large randomized controlled trials (RCTs) on this topic. The variety of current studies differ in their chosen surgical and interventional methods, patient selection criteria, approaches to antiplatelet therapy, and one-stop vs. staged approaches. While further research is needed to evaluate its long-term benefits fully, the interim results indicate positive outcomes regarding graft patency and survival rates.

2.2. Minimally Invasive Valve Surgery (MIVS)

Valve surgery has experienced a significant evolution within the domain of cardiac surgery due to the extensive adoption of minimal access techniques [16][21]. The initial reports on minimally invasive valve repair and replacement techniques came from prominent figures such as Cohn, Cosgrove, Carpentier, Chitwood, and Mohr during the mid to late 1990s [56][57][58][59][60][61][62]. These techniques encompass a range of approaches, from right lateral thoracotomy (with optional rib resection) and mini- or hemi-sternotomy to more advanced methods like video-assisted repair, port-access procedures, and fully robotic valve surgeries [56][57][58][59][60][61][62]. In aortic or mitral surgery, MICS includes a variety of approaches, utilizing specialized technology, tailored vascular entry for CPB perfusion, improved visualization techniques, reduction in the size of cannulas, and providing increased stability and minimizing intrusion into the surgical field [63][64][65][66]. Venous access for CPB in MICS could be performed through direct central right atrium cannulation and peripheral percutaneous femoral or jugular cannulation with vacuum-assisted venous drainage [66][67]. Arterial access can be achieved through central direct cannulation of the aorta, peripheral axillary, or femoral cannulation, percutaneously or via a small incision [64][68]. The surgeon's preference often determines the choice of cannulation technique. However, femoral arterial cannulation and the consequent retrograde perfusion have been reported in various studies to be associated with an increased risk of neurological events, especially in patients with preexisting vascular diseases [22][69][70]. In contrast, central cannulation and antegrade perfusion are often associated with a lower risk of cerebrovascular accidents and groin-related complications [64][71].

Regarding femoral cannulation, the trend is toward percutaneous cannulation and arterial closure devices to reduce groin complications such as wound infections and seromas [72][73]. Nonetheless, large RCTs on this topic are still lacking, and there are single-center studies supporting both percutaneous and direct cannulation with groin incision as safe methods with low complication rates [73][74].

Two specific techniques for aortic occlusion and cardiac protection have been utilized: the transthoracic aortic clamp and endo-aortic balloon occlusion [75][76]. A recent analysis of compared outcomes from the STS database for MV surgery between 2017 and 2018 showed that the use of endo-aortic balloon occlusion (EABO) was similar to external aortic occlusion in most significant outcomes, including mortality and the efficacy of mitral valve repair [77]. Additionally, MICS has introduced carbon dioxide in the operative area to reduce the risk of air embolism, effectively decreasing intracardiac air volume and mitigating this potential complication.

Adapting MICS techniques in valve surgery has raised concerns that aiming for smaller incisions may compromise patient safety by reducing the visibility provided by MS with established long-term outcomes. MICS techniques offer superior cosmetic results to minimize invasiveness and surgical trauma, but also, compared to the conventional MS approach, are associated with a low postoperative complication rate and comparable short- and long-term results [16][21].

2.3. Minimally Invasive Aortic Valve Surgery (MIAVS)

In the execution of MIAVS, the most commonly employed techniques are the partial upper mini-sternotomy and the right anterolateral thoracotomy approach. On the other hand, the parasternal method and transverse sternotomy are utilized less frequently [78][79][80][81][82][83]. The use of a right upper mini-sternotomy approach, also known as the “J” incision or reversed “L” incision, was pioneered by Cohn et al. in 1997 for aortic valve surgery, followed by the introduction of the “L” incision by Svenson et al. and the reversed “T” partial sternotomy by Gundry et al. [78][82][83]. The partial mini-sternotomy involves a small midline skin incision followed by a deviation of part of the sternum. The partial sternotomy can be made on the patient’s right side (“J” sternotomy), left side (“L” sternotomy), or horizontally (inverted “T” mini-sternotomy) [78][82][83]. Other techniques, such as the lower half T-shaped partial sternotomy, “I” mini-sternotomy, and upper V-type mini-sternotomy, are recognized and implemented by certain surgeons but have lost popularity [84][85][86]. Alongside the evolution of partial mini-sternotomy techniques, various surgical approaches have emerged that do not involve sternal deviation. These include procedures with or without video assistance, such as right anterior or right anterolateral thoracotomy and right infra-axillary thoracotomy [84][85]. Entry into the chest cavity is made through the intercostal space, expanded with either a soft tissue retractor or chest retractor. As previously described, the procedures involve CPB, aortic clamping, and cardioplegia. Special instruments like knot pushers and devices for replacing hand-tied surgical knots have become widely used in MIVS. Multiple studies have substantiated the advantages of MIAVS over conventional MS, including shorter recovery time and hospital stay, reduced blood loss and transfusions, lower infection and AF rates, decreased morbidity and mortality, acceptable cardiopulmonary bypass time, and no differences in neurological outcomes and the quality of myocardial protection [12][86][87][88][89]. Furthermore, MIAVS presents a viable alternative in cases of previous cardiac surgery, providing access with fewer adhesions and, particularly in cases of prior CABG, a safe option to avoid graft injury [90]. A meta-analysis by Chang et al. compared results from MIAVS (through upper mini-sternotomy or right anterior thoracotomy) vs. conventional aortic valve replacement via MS, reporting a lower rate of postoperative atrial fibrillation (0.35 to 0.63; $p < 0.001$) and a shorter hospital stay (0.8 (0.4 to 1.3) days; $p < 0.01$) in the MIAVS group, as well as longer CPB times (12.4 min (range, 5 to 19)) [11]. Similarly, the meta-analysis by Brown et al., analyzing 2054 cases of port-access surgery and 2532 cases of MS, showed additional benefits of shorter ventilation times and less blood loss within 24 h (−2.1 h and −79 mL, respectively) in the minimally invasive cohort [12]. The meta-analysis by El-Andari et al. included 48,606 patients who underwent aortic valve replacement and analyzed the advantages of MIAVS via mini-sternotomy or right anterior thoracotomy over aortic valve surgery through MS [91]. The study reported significantly lower in-hospital and 30-day mortality in the MIAVS group compared to the MS group ($p = 0.02$ and $p = 0.0006$, respectively), reduced rates of renal complications ($p < 0.00001$ MS in comparison to port-access surgery and $p < 0.0001$ MS in comparison to right anterior thoracotomy approach), and fewer wound infections ($p = 0.02$ MS in comparison to port-access surgery and $p < 0.00001$ MS in comparison to right anterior thoracotomy approach) [91]. ICU duration and hospital stay were significantly shorter ($p = 0.0001$ and $p < 0.0001$) in the MIAVS group [91]. Phan et al. analyzed 12,786 patients in RTC and non-RTC studies. They reported reduced perioperative deaths in the MIAVS group compared with the conventional MS arm (1.9% vs. 3.3%), fewer renal failure rates (2.5% vs. 4.2%), lower transfusion incidence (36.0% vs. 52.4%), and shorter intensive care stay (−0.60 days) and hospitalization duration (−0.60 days) in the MIAVR group, with a similar mortality rate compared to the conventional group via MS [13]. El-Sayed Ahmad et al. reported 100 cases of video-assisted MIAVS via right anterior thoracotomy with the absence of intraoperative conversion rate to MS, postoperative cerebrovascular events, rethoracotomy for bleeding, and valve-related reoperation and no cases of death in a 30-day follow-up [92]. Olds et al. compared 503 cases of MS, partial upper sternotomy, and right anterior thoracotomy for AV replacement and demonstrated superior results in shorter bypass times (82 (IQ 67–113) minutes vs. 117 (93.5–139.5) vs. 102.5 (85.5–132.5), $p < 0.0001$), a lower incidence of prolonged ventilator support (3.75% vs. 9.17 and 12.9%, respectively ($p = 0.0034$)), shorter ICU hospitalization (6 (IQ 5–9) days vs. 7 (5–14.5) vs. 9 (6–15.5), respectively ($p < 0.05$)) [24]. The 30-day mortality was lowest in the thoracotomy group (1.5%), followed by the partial upper sternotomy group (1.67%), and was the highest in the MS group (5.17%) [24]. Bakhtiary et al. analyzed 513 cases of video-assisted anterior thoracotomy and reported a 1.5% rate of cerebrovascular events, 1.4% rate of pacemaker postoperatively, 0.4% of paravalvular leak, 0.2% rate of conversion to MS, rethoracotomy rate of 2.1%, 0.6% rate of wound infections, 0% intraoperative mortality rate, 0.4% 30-day mortality rate, and 1.4% mortality rate for the total follow-up [93]. Similarly, Hussain et al. reported lower rates of renal failure (OR: 0.52; 95% CI 0.37 to 0.73, $p < 0.001$) and new-onset AF (OR: 0.78; 95% CI 0.67 to 0.90, $p < 0.001$) in the MICVS group, as well as reduced prolonged intubation (OR: 0.50; 95% CI 0.29 to 0.87, $p = 0.01$), shorter ICU stay (−0.42; $p < 0.001$), shorter time to discharge (−2.79; $p < 0.001$), and reduced mortality (OR: 0.58; 95% CI 0.38 to 0.87, $p < 0.01$) [94]. The presented study results suggest that MIAVS has slightly superior short-term results over the MS approach for aortic valve surgery. However, it is essential to note that these findings could be significantly skewed by variables such as the bias in patient selection and the surgeon's enthusiasm, expertise, and reputation, mainly when reporting on novel minimally invasive surgical techniques. Given the absence of solid evidence, there is a need for future prospective RCTs to directly compare the mini-sternotomy and lateral thoracotomy approaches to determine their relative benefits and risks conclusively.

2.4. Minimally Invasive Aortic Surgery (MIAS)

Significant progress in minimally invasive aortic root and arch surgery has been made with the emergence of the partial upper sternotomy approach. Upon establishing the safety and feasibility of partial sternotomy for aortic valve surgery, further advancements have been made in its application within complex aortic surgical procedures for treating the aortic root, ascending aorta, and aortic arch.

Aortic root surgeries with valve replacement (Bentall procedure), reimplantation (David procedure), or remodeling (Yacoub procedure) are challenging operations due to their technical demands and complexity, as well as the need for an experienced surgeon to perform the procedure.

Nevertheless, Mikus et al. presented a series of 53 patients undergoing Mini-Bentall through partial upper surgery with direct central atrial and venous cannulation [95]. Compared to a selected subgroup of 112 patients undergoing Bentall procedures via MS during the same period, Mini-Bentall showed slight superiority in terms of postoperative outcomes, with shorter operative times, a lower incidence of atrial fibrillation, reduced postoperative ventilation times, and 0% in-hospital mortality [95]. Shah et al. compared in-hospital results and 1- and 3-year mortality for 48 patients who underwent Mini-Bentall and 49 who underwent the Bentall procedure via MS between 2009 and 2019 [23]. The Mini-Bentall group had significantly shorter ventilation times (5.5 h vs. 17 h, $p < 0.001$) and fewer reoperations for bleeding (0% vs. 8.2%, $p = 0.043$) [23]. There were no substantial differences noted in CPB duration (165 min vs. 164 min $p = 0.619$), aortic cross-clamp times (139 min vs. 137 min $p = 0.948$), or lengths of stay in both the intensive care unit and the hospital (6 days vs. 7 days $p = 0.086$) [23]. Zero mortality rates were documented in both groups at 1- and 3-year follow-ups [23]. The review by Sef et al. encompassed various non-randomized observational and comparative studies, highlighting outcomes of the David procedure performed via partial or full sternotomy with central arterial and either central or peripheral venous cannulation [96]. Thirty-day mortality ranged from 0% to 3.3% [96]. Several studies noted reduced requirements for blood products and a relatively shorter ICU stay, averaging between 1.1 and 3 days [96]. Additionally, most studies reported favorable early echocardiographic outcomes, with postoperative aortic insufficiency of grade 1 or less seen in 84.6% to 100% of patients [96].

In another extensive study, Harky et al. analyzed 2765 patients who underwent aortic root surgery in minimally invasive technique or MS across eight comparative studies [14]. Their findings indicated that the minimally invasive approach showed a reduction in CPB time (101.7 ± 33.5 min vs. 109.6 ± 52.9 min, $p = 0.009$), a decrease in blood transfusion rates (1.92 ± 3.17 units vs. 2.75 ± 5.64 units, $p = 0.01$), lower intraoperative mortality (0.411% vs. 1.34%, $p = 0.02$), and shorter stays in intensive care (1.41 ± 1.75 days vs. 2.31 ± 2.28 days, $p = 0.0009$) and the hospital (6.81 ± 3.76 days vs. 7.66 ± 4.41 days, $p = 0.03$) [14]. However, no significant differences were found between the two techniques in aortic cross-clamp time (76.1 ± 24.7 min vs. 78.0 ± 31.5 min, $p = 0.28$), total operation time (252.8 ± 56.3 min vs. 249.7 ± 54.1 min, $p = 0.31$), re-exploration for bleeding, stroke rate, wound infection rate, and duration on mechanical ventilation [14].

Tabata et al. conducted a 5-year follow-up on 128 patients who underwent ascending aortic, aortic arch, and root surgery via upper mini-sternotomy. They compared the results to those of a matched cohort group who underwent aortic operations through MS [97]. The study reported a shorter median length of stay (5 vs. 6 days, $p = 0.020$) and fewer units of red blood cell transfusion (2 vs. 2.5 units, $p = 0.020$) for the minimally invasive group [97]. The 5-year survival rate was 97.2%, with no significant difference between the two groups [97]. Moreover, Svensson et al. conducted a series of studies focusing on minimally invasive ascending aorta surgery, including cases of reoperations [78][98][99]. They reported a shorter postoperative hospital stay for the MIAS group (6.2 vs. 8.2 days; $p = 0.0055$), less postoperative pain, reduced use of intravenous narcotics (morphine 20.6 mg vs. 40.9 mg; $p = 0.0028$), and earlier discharge (5.1 vs. 8.1 days; $p < 0.0001$) [78][98][99]. They also noted low levels of postoperative stroke (0–3.7%), an absence of reoperations, and a 30-day survival rate of 98.5–100% [78][98][99]. In a meta-analysis conducted by Rayner et al., comparing surgery on the ascending aorta and root through both MS and minimally invasive approaches, it was observed that patients undergoing MS experienced extended hospital stays ($p < 0.001$) and prolonged durations in the ICU ($p < 0.001$) [100]. MS patients were also more likely to require reoperation for bleeding ($p = 0.024$) and were more susceptible to renal impairment ($p = 0.019$) [100]. Mortality, stroke, and renal impairment incidence were similar across both groups [100].

Furthermore, pioneering progress was made in the minimally invasive treatment of extensive aortic pathology involving the aortic arch combined with hybrid procedures on the descending aorta via partial upper sternotomy. In a single-center series performing minimally invasive complex aortic procedures, aortic arch repair via upper mini-sternotomy was reported as a safe and effective surgical method, with early and mid-term outcomes comparable to the results obtained with conventional sternotomy [92][101]. Risteski et al. reported that among 123 consecutive patients who underwent aortic arch repair through partial mini-thoracotomy, there was a zero rate of conversion to full sternotomy and an early mortality rate of 3.3%, with permanent and temporary neurological deficits in 4.9% and 8.1% of cases, respectively [101]. Among those who underwent frozen elephant trunk repair (33% of the cohort), the rate of spinal cord injury was 3.3% [101]. After five years, the survival rate was estimated at 80%, and the freedom from reoperation was 96% [101]. Two smaller series on this topic were published by Iba et al. (22 patients) and Goebel et al. (21 patients) [102][103]. Iba et al. reported no early deaths, permanent neurological deficits, or spinal cord injuries; a 5% intraoperative conversion rate to full sternotomy due to bleeding; and a 14% rate of re-exploration due to bleeding [102]. Following this line, Goebel et al. reported no conversions to MS during the initial surgery, a 9.5% rate of rethoracotomy due to bleeding, no permanent strokes, and in-hospital mortality of 4.8% [103]. Even though minimally invasive aortic surgery still lacks a large study series and long-term follow-up, the existing studies suggest that MIAS could be performed safely and with superior early results compared to aortic surgery via MS.

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