

Surgery that looks like transcatheter aortic valve implantation: the transaxillary concept for minimally invasive aortic valve replacement in 1,848 consecutive patients

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Background: The transaxillary (TxA) approach for minimally invasive aortic valve replacement (MICS-AVR) is a sternum-sparing technique that combines surgical valve replacement with virtually no visible scarring. We report institutional outcomes of the first 1,848 consecutive TxA MICS-AVR procedures.

Methods: This retrospective single-center cohort included all consecutive patients undergoing isolated TxA MICS-AVR between January 2019 and June 2026. Patients with active endocarditis, redo surgery, or concomitant procedures were excluded. Primary endpoints were 30-day mortality and major adverse cardiac and cerebrovascular events (MACCEs). Univariable and multivariable logistic regression explored associations with adverse outcomes.

Results: Mean age was 67.7±8.1 years, Society of Thoracic Surgeons Predicted Risk of Operative Mortality (STS-PROM) 1.39%±2.90%, and European System for Cardiac Operative Risk Evaluation II (EuroSCORE II) 1.65%±1.12%. TxA use among surgical treatments for isolated aortic valve disease rose from 18.8% in 2019 to 99.2% in 2025. Mean operative, cardiopulmonary bypass, and cross-clamp times were 132±34, 69±23, and 43±16 minutes. No intraoperative death occurred; 1.6% required conversion to sternotomy. Thirty-day mortality was 0.5%, and MACCE occurred in 1.6%, including stroke in 0.9% and myocardial infarction in 0.5%. In multivariable analysis, mortality associations were strongest for insulin-treated diabetes [odds ratio (OR) 8.56], left ventricular ejection fraction (LVEF) <40% (OR 8.45), and intraoperative transfusion (OR 17.86); corresponding MACCE associations included insulin-treated diabetes (OR 3.06), coronary artery disease (OR 2.46), peripheral arterial disease (OR 3.23), sternotomy conversion (OR 5.33), and transfusion (OR 5.49). These outcomes accompanied rapid institutional adoption of the technique, while operative efficiency remained favorable and the need for sternotomy conversion stayed low throughout the cohort. Given only 10 deaths and 30 MACCEs, multivariable findings should be considered exploratory and hypothesis-generating.

Conclusions: Across 1,848 consecutive procedures, TxA MICS-AVR showed excellent reproducibility and safety. As long-term evidence increasingly supports surgical valve replacement in patients with extended life expectancy, TxA uniquely combines durable surgery with a cosmetic result comparable to transcatheter therapy, offering a scalable and strategically relevant platform for contemporary aortic valve care.

Keywords: Minimally invasive cardiac surgery; aortic valve replacement (AVR); transaxillary access (TxA access)



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Introduction

Aortic valve disease remains among the most common structural cardiac conditions in industrialized nations, and its therapeutic management has undergone profound transformation over the past decade. The progressive extension of transcatheter aortic valve implantation (TAVI) into lower surgical-risk patient populations—underpinned by landmark trial data confirming non-inferiority to open surgical repair—has substantially reconfigured the treatment landscape for aortic valve stenosis (1-5). The annual reports of the German Society for Thoracic and Cardiovascular Surgery serve as a sobering quantitative reflection of this shift, documenting a sustained contraction of conventional surgical aortic valve replacement (AVR) volumes by approximately one-third over the preceding decade as a direct consequence of expanding TAVI indications (6). In this competitive environment, the strategic adoption of minimally invasive surgical approaches offers cardiac surgery a credible pathway to preserve clinical relevance and appeal to an increasingly quality-conscious patient population.

The umbrella term “minimally invasive aortic valve surgery” (MICS-AVR) subsumes a broad and heterogeneous array of operative strategies, each differing in incision geometry, thoracic access and cannulation philosophy (7). Historically, its origins date to the early 1990's: Rao and Kumar [1993] were among the first to describe aortic valve replacement through a right-sided thoracotomy, while Cosgrove and Sabik [1996] pioneered the combination of reduced sternal access with femoral cannulation—a configuration that set the conceptual template for subsequent development (8,9). In the years that followed, a variety of partial sternotomy variants proliferated, encompassing ‘J’-, ‘T’-, ‘H’-, ‘inverted T’- and ‘reversed C’-ministernotomies, each representing a modification of sternal access yet invariably imposing some degree of osseous trauma on the patient (7,10-13).

A meaningful advance toward genuinely sternum-sparing surgery came with the adoption of the right anterior thoracotomy (RAT), popularized by Lamelas [2015] as the ‘Miami Method’ and subsequently refined through endoscopically guided right anterolateral thoracotomy by Van Praet *et al.* [2020] (14,15). Together with partial upper ministernotomy (MINISTER), these two access routes emerged as the recognized pillars of mainstream MICS-AVR practice. Meta-analytic synthesis of the available evidence confirms that both RAT and MINISTER constitute safe alternatives to conventional sternotomy, conferring advantages in terms of hospital length of stay, postoperative pain, transfusion requirement and renal outcomes, albeit typically at the expense of marginally prolonged perfusion and aortic cross-clamp times (16,17). Despite this evidence base, procedural adoption remains limited, with MICS-AVR accounting for only 23.0% and 45.0% of surgical aortic valve cases in the United States and Germany, respectively—reflecting persistent structural and educational barriers to widespread implementation (6,18).

In response to these shortcomings, the transaxillary (TxA) concept for MICS-AVR was introduced in 2020 as a sternum-sparing alternative defined by a <5 cm lateral incision within the anterior axillary line, resulting in virtually absent visible scarring (19). A key attribute distinguishing the TxA concept from its predecessors is its procedural versatility: within a single, highly standardized operative framework, the same access route accommodates isolated and combined aortic, mitral and tricuspid valve procedures, selected ascending aortic interventions, atrial septal defect closures, resection of cardiac tumors and even selected cases of endocarditis—reinstating

the ‘one-access concept’ previously reserved for conventional sternotomy within the domain of minimally invasive cardiac surgery (19-26). Early comparative data documented equivalent clinical safety between TxA-MICS-AVR and full sternotomy, and subsequent head-to-head comparison confirmed comparable outcomes between TxA and the established RAT approach (20,21,27).

Building upon this foundational evidence, our group recently published the outcomes of the first 1,000 consecutive TxA isolated MICS-AVR procedures, confirming procedural safety and reproducibility across a broad patient spectrum, with 0.0% intraoperative mortality, 0.9% 30-day mortality, a 0.9% clinically overt stroke rate and a 1.9% overall conversion rate (7). Institutional adoption proved equally compelling, with TxA utilization rising from 18.8% in 2019 to 97.8% by 2023 and a concomitant 20% increase in referral volumes for surgical aortic valve replacement (7). While these findings validated the TxA concept as a clinically sound and scalable approach, an important contextual consideration warrants emphasis: to date, the TxA concept for isolated aortic valve replacement has been described and systematically evaluated almost exclusively by our group. As a consequence, the entirety of published evidence on TxA MICS-AVR—including comparative safety data, procedural benchmarks and multivariable risk characterization—is derived from this single institutional experience. In this light, the continuous expansion of the patient cohort is not merely an institutional milestone but a scientific necessity: each incremental increase in sample size materially strengthens the evidentiary foundation upon which clinical adoption, guideline positioning and patient counselling for this technique must rest. The present analysis, encompassing 1,848 consecutive patients, therefore represents both an update and the most comprehensive dataset available for this access route in the contemporary literature.

Methods

Patient population

Between January 2019 and June 2026, a total of 2,294 patients underwent elective isolated aortic valve procedures at our institution. Of these, 1,848 (80.6%) received TxA aortic valve replacement, while the remaining 446 (19.4%) were treated via alternative surgical access routes: full median sternotomy (n=97), MINISTER (n=183) and RAT (n=166). The first TxA MICS-AVR at University Heart Center Dresden was performed in January 2019, which constitutes the index date of the study period. The distribution of surgical access routes across the entire institutional aortic valve program—including the pre-TxA era from 2014 onwards—is illustrated in *Figure 1*, documenting the progressive displacement of sternotomy, MINISTER and RAT by the TxA approach and providing the full procedural context for the present series.

The present analysis encompasses the first 1,848 consecutive patients undergoing isolated TxA MICS-AVR and thus represents an updated expansion of a previously published 1,000-patient institutional series (7). The study database was locked on June 2nd 2026. The final institutional adoption rate of 99.2% refers to calendar year 2025—the last complete 12-month period within the observation window. Patients with active or recent infective endocarditis, those requiring redo cardiac surgery and individuals undergoing concomitant cardiac procedures were systematically excluded. Cosmetic

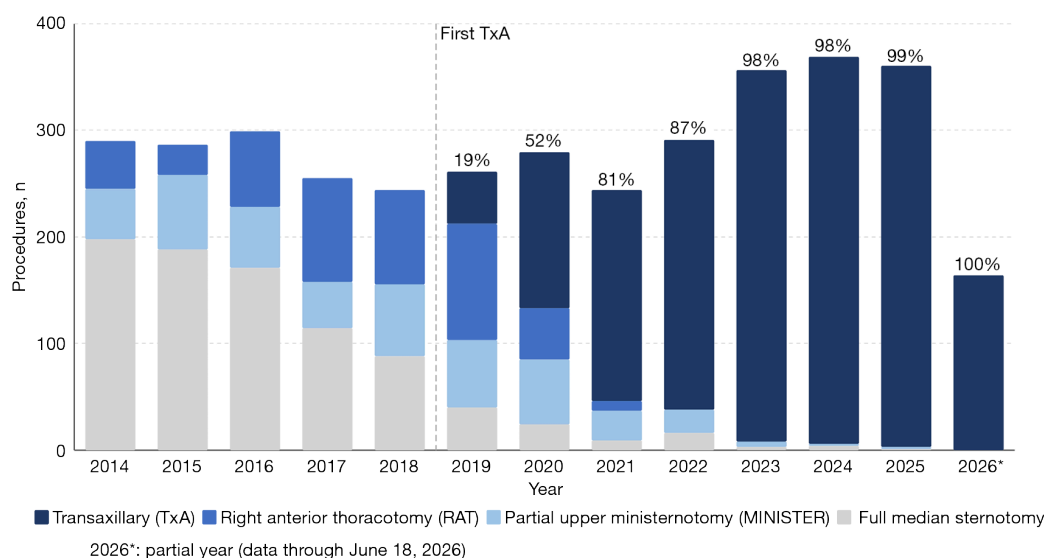


Figure 1 Evolution of surgical access route distribution for isolated aortic valve replacement at the University Heart Center Dresden, 2014–2026. The proportion of TxA cases among all surgical AVR procedures is indicated above each bar from the year of introduction [2019] onwards. AVR, aortic valve replacement; TxA, transaxillary.

outcome was assessed by intraoperative measurement of incision length. Results are reported as mean $\pm$ standard deviation.

Throughout the study period, prospective screening for the most appropriate surgical access route followed a predefined hierarchical algorithm: TxA access was prioritized as the first-line approach; in anatomically unsuitable candidates, RAT was considered as the second option, followed by MINISTER as the third, with full median sternotomy reserved exclusively as a bail-out strategy.

Preoperative planning for all patients included a standardized computed tomography (CT) angiography of the chest, abdomen and pelvis—performed according to the institutional TAVI-CT protocol—to assess aortic root morphology, thoracic anatomy and iliofemoral vessel suitability. This imaging served exclusively as a planning instrument to guide cannulation strategy, prosthesis sizing and operative approach, rather than as a formal screening tool to define exclusion from TxA access. Throughout the early phase of the program, a number of anatomical constellations—including severely vertical aortic orientation, large chest-aortic annulus distance (>15 cm), unfavorable chest wall geometry or borderline iliofemoral vessel caliber (<6 mm)—were treated as relative contraindications and prompted allocation to an alternative access route. However, with accumulating operative experience and progressive refinement of the technique, each of these relative contraindications—except a true porcelain aorta or severe lung adhesions—was systematically overcome. The 100% TxA utilization rate observed among all isolated surgical AVR procedures in 2026 provides the most unambiguous reflection of this evolution: at the current stage of program maturity, no SAVR-suitable anatomical or clinical constellation encountered in the elective isolated aortic valve population has precluded successful execution of the TxA approach.

Study design and ethical statement

This investigation is a single-center retrospective observational cohort study. Clinical data were entered into the institutional database and subsequently retrieved for analysis. The study protocol received approval from the responsible Institutional Review Board (EK-Nr. 298092012), and the analysis was conducted in accordance with the ethical principles of the Declaration of Helsinki. Written informed consent for the publication of patient photographs was obtained from the individuals depicted.

Statistical analysis

All statistical computations were performed using SAS JMP Pro 17.0 (SAS Institute, Cary, NC, USA) in conjunction with the R statistical environment (version 4.2.1; R Foundation for Statistical Computing, Vienna, Austria). Normally distributed continuous variables are reported as arithmetic means with standard deviations; categorical variables are expressed as absolute frequencies and corresponding percentages. Primary endpoints comprised 30-day all-cause mortality and the composite major adverse cardiac and cerebrovascular event (MACCE) endpoint, defined as death, stroke or myocardial infarction within 30 days. Stroke was operationally defined as an acute neurological deficit (modified Rankin Scale ≥ 2) persisting beyond 24 hours confirmed by CT or magnetic resonance imaging. Acute kidney injury (AKI) was defined according to Kidney Disease: Improving Global Outcomes (KDIGO) criteria. Low cardiac output syndrome (LCOS) was defined as the requirement for inotropic support for more than 24 hours postoperatively or the implantation of a mechanical circulatory support device. Respiratory failure was defined as the need for reintubation or mechanical ventilation beyond 24 hours. Delirium was diagnosed using the Confusion Assessment Method for the intensive care unit (CAM-ICU). Surgical site infection (SSI) was defined according to Centers for Disease Control and Prevention (CDC) criteria. Missing data were not imputed; denominators for individual variables reflect available cases and are reported accordingly.

Univariable and multivariable logistic regression analyses were performed to identify predictors of 30-day mortality and MACCE. Univariable results are reported for all candidate variables (*Table 1*); variable selection for the multivariable models was based on a priori clinical reasoning rather than statistical screening. For the 30-day mortality model, the following covariates were prespecified: diabetes mellitus on insulin, left ventricular ejection fraction (LVEF) $< 40\%$, and intraoperative blood transfusion. For the MACCE model: diabetes mellitus on insulin, coronary artery disease, peripheral artery disease, conversion to sternotomy, and intraoperative blood transfusion. Given the low number of events per variable (EPV 3.3 for mortality, 6.0 for MACCE), both models are considered exploratory and results should be interpreted with appropriate caution. Model fit was satisfactory for both models [mortality: Akaike information criterion (AIC) 115.6, deviance reduction 16.8; MACCE: AIC 293.3, deviance reduction 25.5]; all variance inflation factors were < 1.10 , indicating no relevant multicollinearity.

Table 1 Univariable logistic regression—predictors of 30-day mortality and MACCE

Variable	30-day mortality			MACCE		
	OR	95% CI	P	OR	95% CI	P
Age	1.08	0.98–1.19	0.131	1.04	0.99–1.09	0.149
Male sex	0.21	0.03–1.69	0.179	0.58	0.25–1.37	0.248
BMI	0.99	0.88–1.11	0.818	0.95	0.88–1.02	0.183
Diabetes mellitus on insulin	9.30	2.36–36.61	0.009	4.40	1.64–11.80	0.010
Preoperative pacemaker	–	–	>0.999	–	–	>0.999
NYHA class III or IV	4.52	1.16–17.53	0.038	3.39	1.60–7.16	0.001
Bicuspid aortic valve	–	–	>0.999	0.93	0.22–3.94	>0.999
Aortic regurgitation > mild	6.33	1.78–22.56	0.005	1.80	0.82–3.97	0.159
Mixed aortic valve disease	3.49	0.90–13.61	0.089	2.05	0.83–5.06	0.134
Mitral regurgitation > mild	6.54	1.67–25.64	0.021	3.08	1.16–8.19	0.036
Mitral stenosis > mild	–	–	>0.999	–	–	>0.999
Tricuspid regurgitation > mild	3.97	0.49–31.97	0.245	4.10	1.20–13.97	0.048
LVEF <40%	7.56	2.11–27.08	0.006	1.72	0.59–5.00	0.306
Pulmonary hypertension	1.97	0.42–9.34	0.315	1.58	0.60–4.18	0.376
Coronary artery disease	2.32	0.60–9.01	0.198	3.19	1.50–6.78	0.004
Peripheral artery disease	2.65	0.33–21.18	0.340	4.99	1.86–13.43	0.006
Previous stroke	4.33	0.54–34.88	0.228	2.81	0.65–12.18	0.176
EuroSCORE II	1.25	0.83–1.88	0.288	1.11	0.83–1.48	0.473
STS-PROM	1.00	0.77–1.29	0.981	0.99	0.83–1.18	0.923
Carotid stenosis >50%	–	–	>0.999	1.46	0.19–10.96	0.509
COPD	–	–	>0.999	0.86	0.12–6.41	>0.999
Chronic renal disease	2.75	0.77–9.78	0.114	1.77	0.80–3.90	0.164
Conversion to sternotomy	29.87	7.32–121.95	<0.001	7.66	2.19–26.84	0.011
Surgical time	2.13	1.24–3.66	0.006	1.69	1.11–2.57	0.014
CPB time	1.01	0.99–1.03	0.179	1.01	1.00–1.02	0.082
Aortic cross-clamp time	1.01	0.98–1.05	0.479	1.02	1.00–1.03	0.086
Valve malposition	–	–	>0.999	1.81	0.24–13.67	0.439
Multiple aortic clamping	–	–	>0.999	1.46	0.19–10.96	0.509
Prosthesis exchange	–	–	>0.999	1.76	0.23–13.26	0.448
Intraoperative blood transfusion	16.91	1.98–144.08	0.068	11.73	2.48–55.41	0.018

BMI, body mass index; CI, confidence interval; COPD, chronic obstructive pulmonary disease; CPB, cardiopulmonary bypass; EuroSCORE, European System for Cardiac Operative Risk Evaluation; LVEF, left ventricular ejection fraction; MACCE, major adverse cardiac and cerebrovascular event; NYHA, New York Heart Association; OR, odds ratio; STS-PROM, Society of Thoracic Surgeons Predicted Risk of Operative Mortality.

Intraoperative setup and surgical technique

The operative technique applied throughout the study period has been described in detail in prior publications and is summarized here for reference (7,21,28). In brief, a skin incision of 4 to 6 cm is placed along the anterior axillary line, providing access to the third or fourth intercostal space. Cardiopulmonary bypass is established via femoral cannulation, performed either through open surgical cut-down or a fully percutaneous technique depending on individual vessel anatomy. Following pericardial fat resection, the pericardium is opened longitudinally and secured with stay sutures to achieve adequate operative exposure. Left ventricular decompression is ensured through a venting catheter introduced via the right superior pulmonary vein. Aortic valve replacement is subsequently performed according to standardized operative principles. Upon procedural completion, patients are transferred to the intensive care unit for early postoperative extubation.

Results

Patient baseline characteristics

The study population comprised 1,848 consecutive patients. Mean age was 67.7±8.1 years, with a predominance of male patients (n=1,224; 66.2%). Preoperative risk stratification classified the population as low surgical risk, with a mean Society of Thoracic Surgeons Predicted Risk of Operative Mortality (STS-PROM) of 1.39% ±2.90% and a mean European System for Cardiac Operative Risk Evaluation (EuroSCORE) II of 1.65%±1.12%. Left ventricular systolic function was preserved with a mean LVEF of 56.1%±10.0%. Sievers type 0 bicuspid aortic valve anatomy was documented in 134 cases (7.3%). Echocardiographic parameters reflected predominantly obstructive pathology, with a mean aortic valve area of 0.73±0.16 cm², mean peak gradient of 74.5±20.6 mmHg and mean gradient of 45.8±13.6 mmHg. Severe aortic stenosis was the primary indication in 1,656 patients (89.6%), while severe regurgitation as the primary indication was documented in 192 cases (10.4%). Relevant comorbidities included coronary artery disease in 289 patients (15.6%), chronic kidney disease in 365 (19.8%), insulin-dependent diabetes in 84 (4.5%) and COPD in 69 (3.7%). Pulmonary hypertension was present in 209 patients (11.3%). Compared with the previously reported initial 1,000-patient series, the overall risk profile of the expanded cohort remained stable, confirming consistent patient selection criteria throughout the observation period (7). *Table 2* summarizes patient baseline characteristics in full.

Table 2 Patient baseline characteristics (n=1,848)	
Variable	Values
Baseline demographics	
Age (years)	67.7±8.1
Table 2 (continued)	

Table 2 (*continued*)

Variable	Values
Male sex	1,224 (66.2)
BMI (kg/m ²)	28.9±5.4
EuroSCORE II (%)	1.65±1.12
STS-PROM (%)	1.39±2.90
Valvular pathology	
Sievers Type 0 bicuspid aortic valve	134 (7.3)
Primary indication aortic stenosis—severe	1,656 (89.6)
Primary indication aortic regurgitation—severe	192 (10.4)
Mitral regurgitation (> mild)	116 (6.3)
Tricuspid regurgitation (> mild)	52 (2.8)
Comorbidities	
Coronary artery disease	289 (15.6)
Peripheral arterial disease	75 (4.1)
Carotid stenosis	43 (2.3)
Previous stroke	37 (2.0)
Pulmonary hypertension	209 (11.3)
Diabetes mellitus on insulin	84 (4.5)
Chronic renal disease	365 (19.8)
COPD	69 (3.7)
Preoperative pacemaker	40 (2.2)

Values are mean ± standard deviation or n (%). BMI, body mass index; COPD, chronic obstructive pulmonary disease; EuroSCORE, European System for Cardiac Operative Risk Evaluation; STS-PROM, Society of Thoracic Surgeons Predicted Risk of Operative Mortality.

Procedural data

Mean skin-to-skin operative time was 132±34 minutes, cardiopulmonary bypass duration averaged 69±23 minutes, and the aortic cross-clamp interval measured 43±16 minutes. Sutureless and rapid-deployment prostheses constituted the dominant implant category: the Perceval Plus® (Corcym; n=1,142; 61.8%) and Perceval® (Corcym; n=216; 11.7%) together accounted for the majority of implants, alongside the Intuity Elite® (Edwards; n=56; 3.0%). Conventional sutured porcine (n=206; 11.1%) or bovine (n=102; 5.5%) bioprostheses were implanted in a substantial minority. Mechanical prostheses were selected in a minority of cases (n=120; 6.5%). Three prostheses remained unclassified due to insufficient documentation, two Perceval valves were used with sutures and one Edwards Sapien S3 valve was used off-label. Mean prosthesis size was 24.2±2.1 mm. Intraoperative events were infrequent: repeated aortic cross-clamping was required in 43 cases (2.3%), valve malposition occurred in 35 (1.9%), need for intraoperative prosthesis exchange in 37 (2.0%) and intraoperative blood transfusion in 14 patients (0.8%). No patient sustained an intraoperative death. Conversion to

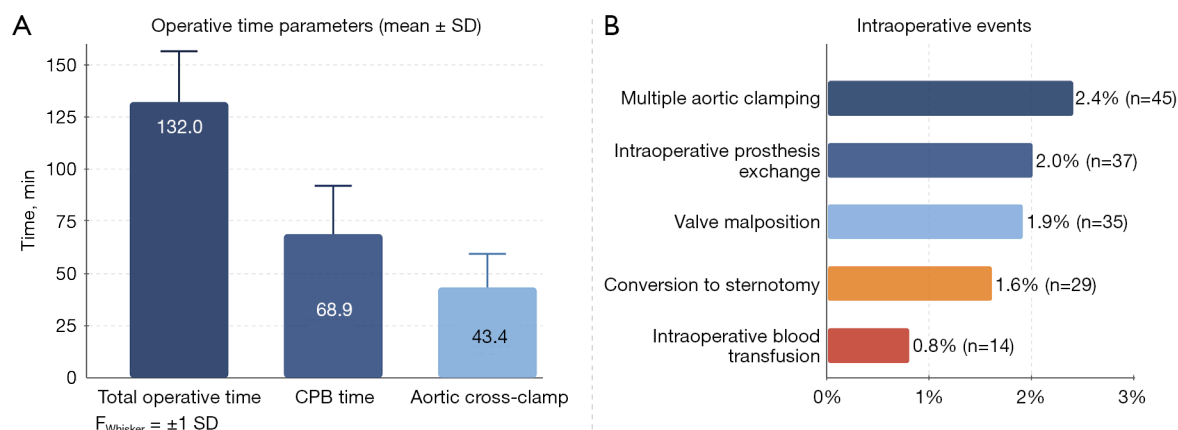


Figure 2 Procedural time parameters and intraoperative events. (A) Mean operative, CPB, and aortic cross-clamp times. (B) Frequency of intraoperative events, displayed as percentage of the total cohort. CPB, cardiopulmonary bypass; SD, standard deviation.

sternotomy or MINISTER was required in 29 patients (1.6%). *Figure 2* and *Table 3* summarize procedural parameters.

Postoperative outcomes

Mean total hospital stay was 8.9 ± 5.7 days, with a mean intensive care unit stay of 1.5 ± 2.4 days. Ten patients died within 30 days of the index procedure, corresponding to a 30-day mortality rate of 0.5% ($n=10/1,848$). The composite MACCE endpoint was reached in 30 patients (1.6%), encompassing postoperative stroke (modified Rankin Scale ≥ 2) in 17 cases (0.9%) and myocardial infarction in 9 patients (0.5%). Concurrent occurrence of more than one MACCE component was documented in 6 patients ($n=6/30$; 20.0%). Age-stratified analysis revealed a progressive increase in adverse event rates with advancing age. Among patients younger than 70 years ($n=947$), 30-day mortality was 0.4% and the composite MACCE rate 1.4%. In the intermediate age group of 70 to 75 years ($n=644$), mortality was 0.2% and MACCE 1.1%. Patients older than 75 years ($n=257$) demonstrated the highest event rates, with 30-day mortality of 1.9% and a MACCE rate of 3.9%, reflecting the greater comorbidity burden inherent to this subgroup. Across all age strata, absolute event rates remained low and within the range reported for established minimally invasive access routes. Age-stratified outcomes are illustrated in *Figure 3*.

Recovery during the early postoperative period was generally uncomplicated. *Table 4* summarizes postoperative outcomes. The most frequently observed complication was transient delirium, affecting 200 patients (10.8%). Rethoracotomy for any indication was necessary in 104 cases (5.6%). Permanent pacemaker implantation was required in 78 patients (4.2%). AKI was documented in 54 patients (2.9%), with renal replacement therapy required in 14 (0.8%). Respiratory failure occurred in 25 patients (1.4%), cardiac tamponade in 22 (1.2%), LCOS in 16 (0.9%) and sepsis in 16 (0.9%). Subcutaneous emphysema was documented in 59 patients (3.2%). SSIs were identified in 45 patients (2.4%), with the groin as the predominant anatomical site ($n=23$; 1.2%), followed by the thorax ($n=13$; 0.7%) and combined involvement of both sites ($n=9$;

0.5%). Postoperative blood transfusions were required in 358 patients (19.4%). *Figure 4* illustrates the main postoperative adverse events.

Table 3 Procedural data (n=1,848)

Variable	Values
Total operative time (min)	132.0±34.4
Cardiopulmonary bypass time (min)	68.9±23.3
Aortic cross-clamp time (min)	43.4±16.1
Valve malposition	35 (1.9)
Multiple aortic clamping	43 (2.3)
Intraoperative prosthesis exchange	37 (2.0)
Intraoperative blood transfusion (any)	14 (0.8)
Conversion to sternotomy	29 (1.6)

Values are mean ± standard deviation or n (%).

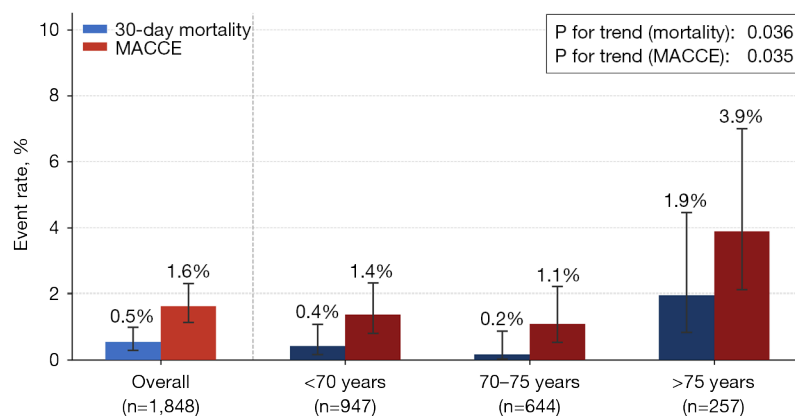


Figure 3 Overall and age-stratified 30-day mortality and MACCE. MACCE, major adverse cardiac and cerebrovascular event.

Table 4 Postoperative outcomes (n=1,848)

Variable	Values
Main clinical endpoints	
Total hospital stay (days)	8.9±5.7
ICU stay (days)	1.5±2.4
MACCE (death + MI + stroke)	30 (1.6)
30-day mortality	10 (0.5)
Postoperative stroke	17 (0.9)
Low cardiac output syndrome	16 (0.9)
Postoperative echocardiography (predischARGE)	
Peak velocity Vmax (cm/s)	233±36
Peak gradient Pmax (mmHg)	22.3±7.0
Mean gradient Pmean (mmHg)	12.2±3.9
Aortic valve area (cm ²)	1.8±0.2
Left ventricular ejection fraction (%)	54.7±8.7
Postoperative morbidity	
Permanent pacemaker implantation	78 (4.2)
Delirium	200 (10.8)
Subcutaneous skin emphysema	59 (3.2)
Surgical site infection	45 (2.4)
Rethoracotomy	104 (5.6)
Cardiac tamponade	22 (1.2)
Postoperative blood transfusion	358 (19.4)
Acute kidney injury	54 (2.9)
Renal replacement therapy	14 (0.8)
Respiratory failure	25 (1.4)
Sepsis	16 (0.9)

Values are mean ± standard deviation or n (%). ICU, intensive care unit; MACCE, major adverse cardiac and cerebrovascular events; MI, myocardial infarction; P, pressure; V, velocity.

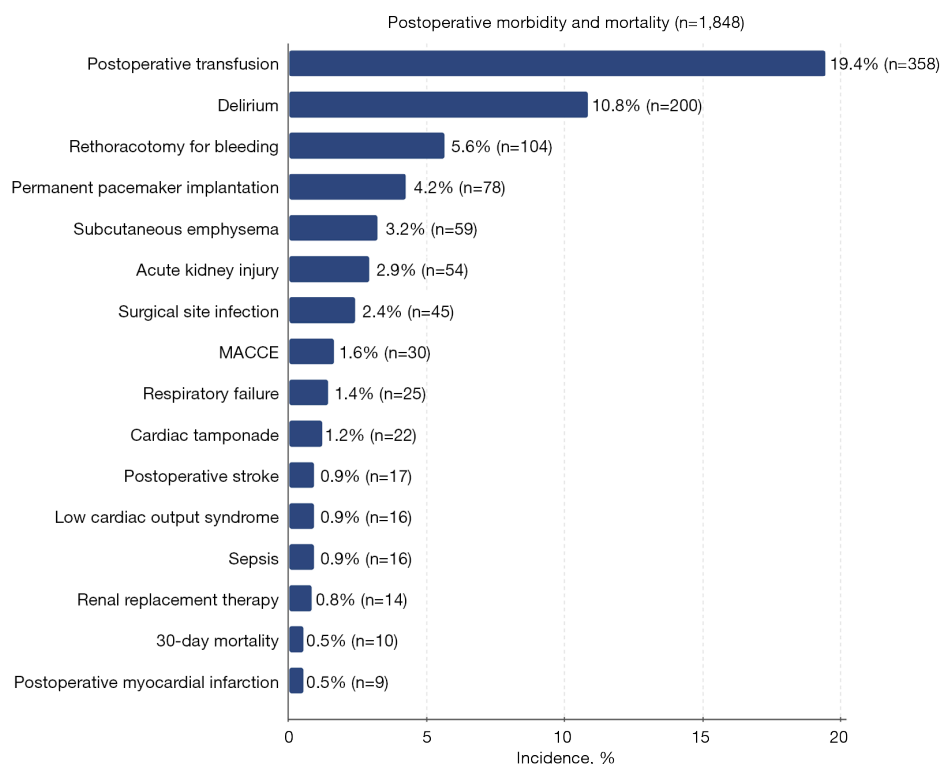


Figure 4 Postoperative morbidity and 30-day mortality. All values are n (%), n=1,848). MACCE, major adverse cardiac and cerebrovascular event.

Predischarge echocardiography demonstrated satisfactory hemodynamic prosthesis function across the cohort, with a mean peak gradient of 22.3 ± 7.0 mmHg, mean gradient of 12.2 ± 3.9 mmHg, aortic valve area of 1.8 ± 0.2 cm² and mean peak velocity of 233 ± 36 cm/s. Postoperative LVEF was $54.7 \pm 8.7\%$. Prosthesis distribution and echocardiographic outcomes are summarized in *Figure 5*.

Outcomes by prosthesis type: sutureless versus sutured valves

Six patients (0.3%), including one Edwards Sapien S3, could not be assigned to either group due to unclassifiable prosthesis documentation and were excluded from subgroup analyses, yielding an evaluable cohort of 1,842 patients (sutureless: n=1,414; sutured: n=428). Aortic cross-clamp time was significantly shorter in the sutureless group (39.4 ± 13.7 vs. 55.6 ± 15.2 min; $P < 0.001$). Thirty-day mortality (0.6% vs. 0.5% ; $P > 0.999$) and MACCE (1.6% vs. 1.4% ; $P > 0.999$) were identical between groups. Postoperative mean gradient was lower in the sutureless group (11.9 ± 3.6 vs. 13.6 ± 4.6 mmHg; $P < 0.001$), as was peak gradient (21.7 ± 6.6 vs. 24.6 ± 8.0 mmHg; $P < 0.001$). The permanent pacemaker implantation rate was 4.6% in the sutureless and 2.8% in the sutured group ($P = 0.129$). *Table 5* shows outcomes stratified by valve type.

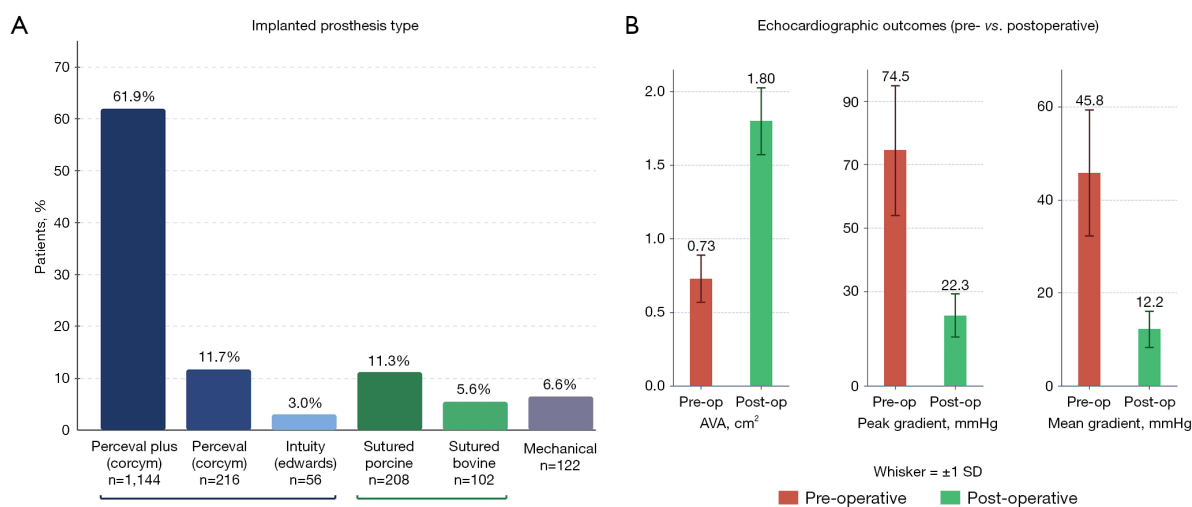


Figure 5 Implanted prosthesis types and echocardiographic outcomes. (A) Distribution of implanted prostheses. Mean prosthesis size was 24.2 ± 2.1 mm. N=6 prostheses are not displayed [sutured Perceval (n=2), Edwards Sapien S3 (n=1) and unclassified (n=3)]. (B) Comparison of preoperative and predischarge echocardiographic parameters. AVA, aortic valve area; SD, standard deviation.

Risk factor analysis for 30-day mortality and MACCE

Univariable screening identified multiple candidate predictors for both MACCE and 30-day mortality, as detailed in *Table 1*. Neither EuroSCORE II nor STS-PROM demonstrated adequate discriminatory capacity for 30-day mortality or MACCE in this cohort. C-statistics were 0.596 [95% confidence interval (CI): 0.327–0.833] and 0.573 (95% CI: 0.342–0.776) for EuroSCORE II and STS-PROM *vs.* mortality, and 0.557 (95% CI: 0.441–0.671) and 0.537 (95% CI: 0.414–0.656) *vs.* MACCE, respectively—all below the conventional threshold of 0.70 and with CIs spanning 0.5.

Given the low absolute event count (n=10 deaths; EPV 3.3), the following multivariable analysis is strictly exploratory and hypothesis-generating, and results should not be interpreted as establishing independent causal risk factors. On multivariable logistic regression, variables associated with 30-day mortality were diabetes mellitus on insulin [odds ratio (OR) 8.56; 95% CI: 2.10–34.93; $P=0.002$], LVEF <40% (OR 8.45; 95% CI: 2.28–31.25; $P=0.001$), and intraoperative blood transfusion (OR 17.86; 95% CI: 1.89–168.80; $P=0.012$). Exploratory associations with MACCE were diabetes mellitus on insulin (OR 3.06; 95% CI: 1.08–8.64; $P=0.035$), coronary artery disease (OR 2.46; 95% CI: 1.09–5.56; $P=0.031$), peripheral arterial disease (OR 3.23; 95% CI: 1.13–9.28; $P=0.029$), and conversion to full sternotomy (OR 5.33; 95% CI: 1.31–21.76; $P=0.020$). Intraoperative blood transfusion showed a borderline association with MACCE that did not reach conventional significance (OR 5.49; 95% CI: 0.97–31.12; $P=0.054$). Given the low number of events per variable in both models (EPV 3.3 and 6.0, respectively), all multivariable results are considered exploratory (*Figure 6*).

Table 5 Outcomes stratified by prosthesis type: sutureless versus sutured valves

Variable	Sutureless (n=1,414)	Sutured (n=428)	P value
Intraoperative			
Surgery time (min)	127.0±32.7	144.9±34.5	<0.001
Aortic cross-clamp time (min)	39.4±13.7	55.6±15.2	<0.001
Repeated cross-clamping	41 (2.9)	2 (0.5)	0.002
Postoperative (30-day)			
30-day mortality	8 (0.6)	2 (0.5)	>0.999
MACCE	23 (1.6)	6 (1.4)	>0.999
Permanent pacemaker implantation	65 (4.6)	12 (2.8)	0.129
Echocardiography (predischARGE)			
Peak gradient (mmHg)	21.7±6.6	24.6±8.0	<0.001
Mean gradient (mmHg)	11.9±3.6	13.6±4.6	<0.001
Aortic regurgitation > trivial	36 (2.5)	8 (1.9)	0.474

Values are mean ± standard deviation or n (%). P values: Mann-Whitney U test for continuous variables; Fisher exact test for categorical variables. Six patients (0.3%) were excluded from this subgroup analysis due to five unclassifiable prosthesis type and Edwards Sapien S3; these are included in the overall cohort (n=1,848). MACCE events in the excluded group account for the discrepancy between subgroup totals and the overall n=30. MACCE, major adverse cardiac and cerebrovascular event (composite of 30-day mortality, myocardial infarction, and stroke).

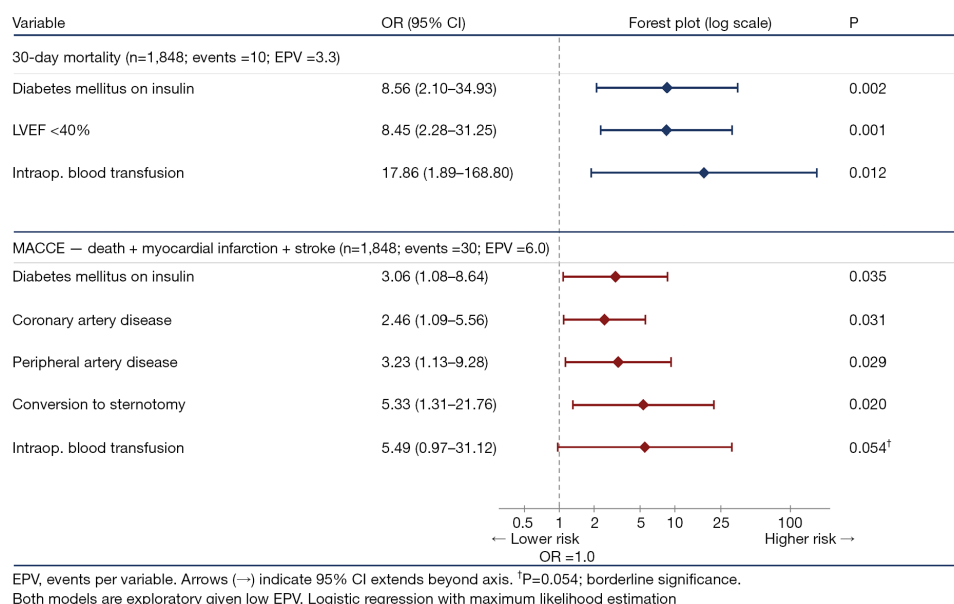


Figure 6 Exploratory multivariable associations with 30-day mortality and MACCEs identified by multivariable logistic regression. CI, confidence interval; EPV, events per variable; LVEF, left ventricular ejection fraction; MACCE, major adverse cardiac and cerebrovascular event; OR, odds ratio.

Learning curve analysis

Learning curve analysis was performed across 1,848 consecutive TxA MICS-AVR procedures from 2019 to 2026, spanning a period of simultaneous program expansion and structured surgical training (*Figure 7*). Thirty-day mortality declined from 2.1% in 2019 to 0% in 2025 and 2026; MACCE followed a parallel but non-monotonic trajectory, peaking at 4.0% in 2021 before falling to 0% in the two most recent years. EuroSCORE II remained stable throughout (1.24–1.84%), excluding progressive risk reduction as an explanatory factor. Aortic cross-clamp time was stable between 2019 and 2024 (41.4–44.5 min) but increased modestly in 2025–2026 (44.9 and 48.8 min, respectively). Conversion to full sternotomy declined from 2.1% to 0.6%, while the rate of repeated cross-clamping increased from 0% to 3.7% without associated 30-day mortality.

Conceptual penetration and referral dynamics

Over the course of the study period, the distribution of surgical access routes across all patients undergoing isolated surgical AVR at our institution evolved markedly. The proportion of TxA cases among all surgical AVR procedures increased from 18.8% at the outset of the observation period to 99.2% in the final complete study year 2025, indicating near-complete institutional adoption of the TxA approach in eligible cases. The full programmatic context is illustrated in *Figure 1*, which displays the annual distribution of all four surgical access routes from 2014 onwards. Prior to TxA

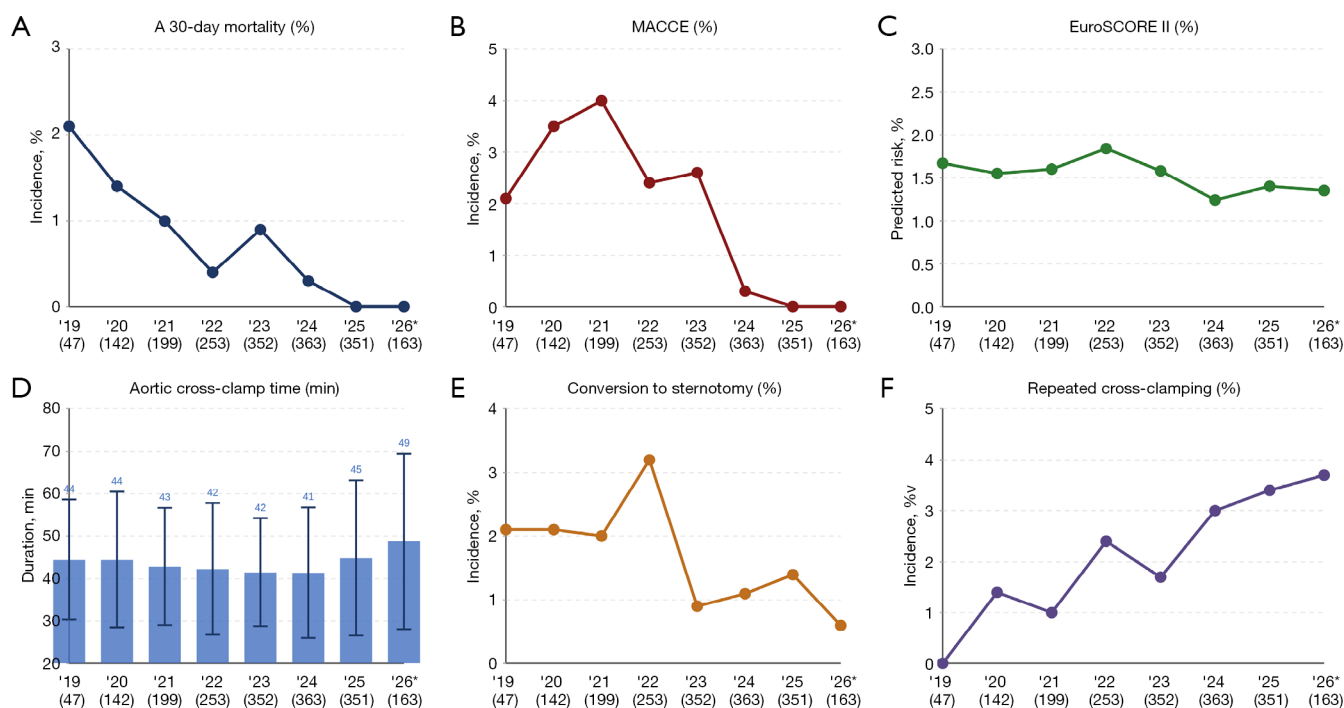


Figure 7 Program level learning curve analysis of TxA MICS-AVR [2019–2026]. *, partial year (data through June 2nd, 2026). MACCE, major adverse cardiac and cerebrovascular event; MICS-AVR, minimally invasive aortic valve replacement; TxA, transaxillary.

introduction, the institutional program was distributed across full median sternotomy, MINISTER and RAT in comparable proportions. Following the first TxA procedure in January 2019, adoption accelerated markedly year on year: 18.8% [2019], 52.3% [2020], 81.1% [2021], 86.9% [2022], 97.8% [2023], 98.4% [2024] and 99.2% [2025]. In the partial year 2026 (data through June 2nd), 100% of isolated surgical AVR procedures were performed via the TxA approach. Concomitantly, RAT was completely abandoned after 2022—with 0 cases recorded thereafter—while MINISTER and full sternotomy were reduced to exceptional indications by 2023. This trajectory reflects not an incremental shift but a complete structural reorganization of the institutional aortic valve program around a single standardized access route. Concomitantly, absolute referral volumes for surgical AVR increased by +24.1% over the study period—a trend inversely aligned with the general national decline documented in registry data (6)—consistent with the hypothesis that broad adoption of minimally invasive techniques may positively influence cardiologist referral behavior (7).

The TxA approach was associated with a favorable cosmetic result. The mean skin incision length measured 4.7 ± 0.6 cm, confined to the anterior axillary line and concealed beneath the upper arm at rest. Representative postoperative photographs illustrating the cosmetic outcome of TxA MICS-AVR versus transfemoral TAVI are provided in *Figure 8*.

Discussion

The present series of 1,848 consecutive patients establishes the TxA concept for MICS-AVR as a mature, reproducible and scalable surgical platform, delivering clinical outcomes that are consistent across an expanded patient spectrum and favorable in comparison with established benchmarks for MICS-AVR. A 30-day mortality of 0.5% in an unselected all-comers population compares favorably with contemporary registry benchmarks for isolated surgical AVR—including an operative mortality of 1.0–2.5%

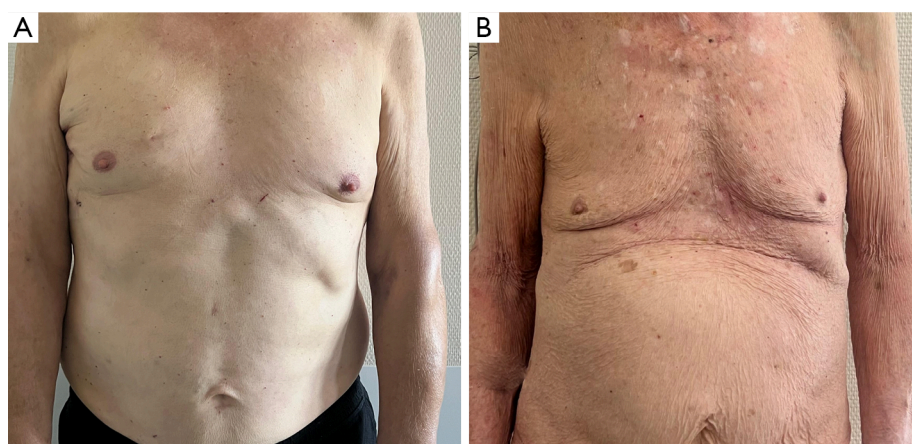


Figure 8 Cosmetic outcome after TxA-MICS-AVR (A) versus transfemoral TAVI (B). MICS-AVR, minimally invasive aortic valve replacement; TAVI, transcatheter aortic valve implantation; TxA, transaxillary.

documented in the German Heart Surgery Report and STS Database analyses—and underscores the safety of TxA MICS-AVR even at institutional scale (6,18).

For more than a decade, the progressive expansion of TAVI into lower-risk patient populations has been driven by randomized controlled trial evidence demonstrating non-inferiority to surgical AVR at follow-up intervals of two to five years and with the NOTION-Trial up to 10 years (1,3-5). These data provided the evidential foundation for guideline recommendations that now endorse TAVI in patients aged 70 years and above with suitable anatomy, irrespective of surgical risk category. Yet the scientific landscape is shifting with increasing momentum, and a critical appraisal of the most recent evidence challenges the uncritical extrapolation of short-term equivalence into long-term therapeutic equivalence—particularly in patients with a life expectancy exceeding 5 years.

Age-stratified analysis of perioperative outcomes in our cohort underscores that rigid age thresholds are an inadequate basis for patient selection in TxA MICS-AVR. Instead, indication should be guided primarily by individual parameters including estimated life expectancy and valve morphology (1). In patients younger than 70 years and in those aged 70–75 years, 30-day mortality rates of 0.4% and 0.2%, respectively, combined with MACCE rates of 1.4% and 1.1%, reflect an exceptional safety profile that is at least comparable—and in part superior—to published outcomes following both conventional surgical aortic valve replacement and transcatheter approaches in similar populations (1,4,6,16,17). These findings support the conclusion that TxA MICS-AVR can be performed with excellent perioperative results across the broad age range typically encountered in surgical valve practice. The picture is more nuanced in patients older than 75 years, where a 30-day mortality of 1.9% and a MACCE rate of 3.9% reflect the elevated baseline risk inherent to this subgroup—a statistically significant progressive increase confirmed across all age strata by formal trend testing ($P=0.036$ and $P=0.035$, respectively)—and highlight the critical importance of individualized, outcome-oriented patient selection within a structured Heart Team framework (1). In this age cohort, a thorough multidisciplinary assessment integrating comorbidity burden, anatomical suitability, and patient preferences is not merely recommended but essential—and the decision to proceed should under no circumstances be driven by chronological age alone.

A landmark Bayesian meta-analysis by Marin-Cuartas *et al.* [2026], synthesizing 5-year outcome data from all available randomized controlled trials comparing TAVI and SAVR in low- to intermediate-risk patients, yielded findings of considerable clinical weight (29). The analysis demonstrated a posterior probability of 99.3% that surgical AVR outperforms TAVI with respect to 5-year all-cause mortality, a posterior probability of 88.0% favoring SAVR for stroke, and a posterior probability of 99.5% favoring SAVR for the composite clinical endpoint (29). Individual 5-year analyses from the PARTNER 3 and Evolut Low Risk trials corroborate these findings at the trial level (4,30,31), while the NOTION trial—the most mature available randomized evidence in lower-risk patients—demonstrated comparable major clinical outcomes at ten years, yet documented a higher incidence of structural valve deterioration following transcatheter implantation (32). These results are consistent with the perspective articulated in a recent Great Debate publication in the European Heart Journal, in which Doenst *et al.* argued that surgical AVR should be considered the first-line treatment for patients with a life expectancy beyond 5 years, citing insufficient

long-term durability data for transcatheter devices, higher rates of procedure-related complications following TAVI, and the availability of surgical bioprostheses with well-characterized long-term performance profiles (33). This position is further supported by the editorial commentary of Borger *et al.*, who—while acknowledging the transformative impact of transcatheter innovation—emphasized the substantial residual uncertainties surrounding TAVI in younger, lower-risk patients and cautioned against premature guideline liberalization in the absence of mature 10-year data (34).

If surgical AVR is to reclaim its position as the preferred treatment strategy for younger patients with extended life expectancy, it must do so on terms acceptable to contemporary patients and the cardiologists who counsel them. The therapeutic experience of conventional median sternotomy—with its associated chest wall trauma, prolonged recovery, visible midline scar and perceived invasiveness—increasingly conflicts with patient expectations shaped by the minimally invasive transcatheter alternative. In pragmatic terms, full sternotomy is becoming progressively difficult to justify to well-informed patients who are aware that a catheter-based option exists, regardless of whether the long-term evidence supports it. The ‘cosmetic benchmark’ established by TAVI has effectively raised the threshold of acceptability for surgical intervention.

Established MICS approaches—MINISTER and RAT—represent meaningful advances in this direction, and the evidence supporting their safety relative to full sternotomy is well documented (16,17). Nevertheless, both access routes retain visible thoracic scars and, despite decades of availability, have failed to achieve broad institutional adoption, with MICS rates of only 23.0% in the United States and 45.0% in Germany (6,18). The as-yet unexplored structural barriers to scaling MINISTER and RAT might explain this persistent implementation gap.

It is precisely within this context that the TxA concept acquires its most compelling strategic rationale (7,35). The TxA approach offers what neither conventional sternotomy nor existing MICS techniques have been able to deliver simultaneously: surgical-grade valve replacement with proven durability, combined with a cosmetic result genuinely comparable to that of TAVI (7,19,21) (*Figure 8*). The lateral axillary incision, concealed within the natural skin folds of the thoracic wall, leaves no visible anterior chest scar, meeting the cosmetic expectations of patients accustomed to the percutaneous aesthetic of transcatheter therapy (7,19,28). In an era of shared decision-making, cosmetic outcome is a legitimate and measurable determinant of therapeutic preference.

Beyond cosmesis, the TxA concept distinguishes itself through a degree of procedural scalability that has no precedent among existing MICS strategies (7). As demonstrated in the present series, TxA access achieved near-universal utilization among all surgical AVR cases by the final study year—without any measurable compromise in clinical safety parameters. The programmatic data presented in *Figure 1* add an important dimension to this observation. The TxA approach did not merely grow alongside existing access routes—it systematically replaced them. RAT, previously the institutional second-line approach, was entirely discontinued after 2022. MINISTER and full sternotomy were reduced to rare exceptions within 3 years of TxA introduction. This pattern of complete competitive displacement is, to our knowledge, without precedent in the history of minimally invasive aortic valve surgery: no previously introduced MICS technique has achieved full substitution of all alternative approaches within a

comparable timeframe at a single high-volume center. That this occurred without any measurable deterioration in clinical outcomes—and in parallel with a 24.1% increase in overall surgical referral volumes—underscores that the TxA concept functions not merely as a technical preference but as a genuine platform standard capable of absorbing the full complexity and volume of an institutional aortic valve program. The parallel increase in institutional referral volumes for surgical AVR is consistent with the hypothesis that a genuinely minimally invasive, cosmetically convincing surgical alternative can positively influence patient and cardiologist decision-making in a way that MINISTER and RAT, despite their clinical merits, have historically not (7). The versatility of the TxA platform reinforces this positioning: a single standardized operative framework enables isolated and combined aortic, mitral and tricuspid valve procedures, selected ascending aortic interventions, atrial septal defect repair and resection of cardiac tumors as well as selected cases of endocarditis (22–27).

The year-by-year outcome analysis reveals a clearly positive overall trajectory, yet notable deviations from a strictly monotonic learning curve—most notably the MACCE peak in 2021 and the modest increase in cross-clamp time in 2025–2026. These patterns are best understood in the context of three parallel processes operating throughout the study period: accumulation of individual operative experience, the progressive integration of junior surgeons into a structured training program, and a deliberate expansion of patient selection criteria. As institutional adoption approached 100%, an increasing proportion of procedures was performed by trainees under supervision, and simultaneously, anatomically and clinically more complex cases were accepted—reflected in a rising mean body mass index (BMI) (27.8 to 29.8 kg/m²), an increasing rate of repeated cross-clamping (0% to 3.7%), and the modest rise in cross-clamp times observed in 2025–2026. These factors cannot be formally disentangled from the primary learning curve in a program-level dataset. Crucially, however, EuroSCORE II remained stable throughout, zero mortality was achieved in both 2025 and 2026, and the conversion rate fell to 0.6%—a constellation of findings that attests not only to the safety and teachability of the TxA approach, but to its scalability across a broadening patient spectrum. True single-surgeon learning curve analysis would require individual operator-level data and is beyond the scope of the present study.

The minimally invasive approach is uniquely complemented by sutureless and rapid-deployment valve technology. Stratification by prosthesis type confirmed equivalent 30-day mortality and MACCE between sutureless and sutured prostheses, and the 16-minute reduction in aortic cross-clamp time with sutureless implants (39.4 *vs.* 55.6 min; $P < 0.001$) represents a meaningful operational advantage in the minimally invasive setting. These advantages notwithstanding, sutureless implantation was associated with a higher rate of repeated aortic cross-clamping (2.9% *vs.* 0.5%; $P = 0.002$), most commonly attributable to valve malposition (2.3% *vs.* 0.7%; $P = 0.042$)—a recognized technical challenge of sutureless deployment that diminishes with increasing experience. The permanent pacemaker rate of 4.6% with sutureless valves—while numerically higher than with sutured prostheses (2.8%, $P = 0.129$)—compares favorably with the 9.1% reported in the largest meta-analysis of sutureless versus conventional aortic valve replacement by Hurley *et al.* (36). Transvalvular gradients were lower in the sutureless group, but formal comparison is, however, limited by the absence of annular sizing data precluding case-matched analysis. These findings are concordant with the PERSIST-AVR randomized trial, which demonstrated non-inferiority of sutureless

versus conventional bioprostheses with respect to MACCE at one year, alongside significantly shorter aortic cross-clamp times—reinforcing the clinical rationale for sutureless valve use in a minimally invasive setting (37).

Benchmarked against established MICS access routes, the TxA approach compares favorably across all major endpoints (20,27). Phan *et al.*, in a meta-analysis of 12,786 MINISTER and RAT patients, reported pooled 30-day mortality of 1.9%, stroke rates of 2.2%, renal failure in 2.5% and respiratory complications in 3.6% (16). The corresponding figures in the present TxA cohort are numerically lower across all of these domains, albeit with the important caveat that direct statistical comparison between unmatched populations is not permissible. These comparisons must be interpreted with caution. The cohorts differ substantially in operative era, patient risk profile, valve pathology distribution, and endpoint definitions, precluding direct equivalence. Our data are best understood as hypothesis-generating—demonstrating that outcomes achievable with the TxA approach are within the range reported for established comparators—rather than as evidence of superiority. Similarly, the head-to-head propensity-matched analysis by Taghizadeh-Waghefi *et al.* documented equivalent perioperative outcomes between TxA and RAT, while TxA demonstrated advantages in recovery-related secondary endpoints (27). Moreover, another series by the same group demonstrated superiority of TxA over the MINISTER approach (20).

The perioperative complication profile compares favorably with published benchmarks—notably in an unselected all-comer population, in contrast to the carefully screened cohorts of the available comparative literature. Postoperative transfusion (19.4%) remained below the 26.7% reported in PARTNER 3 and the 36–52% in the Phan *et al.* MICS meta-analysis (4,16); rethoracotomy (5.6%) was comparable to the 4.7% reported by Phan *et al.*, with chest wall hemorrhage as the predominant etiology (16); delirium (10.8%) was less than half the 23% documented by Petersson *et al.* in a large cardiac surgical meta-analysis and also nearly half compared to 21.6% reported in the prospective FINDERI-study (38,39). SSI (1.2%) fell within the 0.5–1.0% range of large dedicated MICS series (40,41). No femoral arterial dissection, thrombotic occlusion, or limb ischemia occurred. The one domain with identifiable improvement potential is groin wound morbidity, which in this cohort arose predominantly in the context of surgical cut-down cannulation; transition to a fully percutaneous femoral strategy would be expected to reduce this access-specific complication further.

Limitations

The present study is subject to several inherent methodological constraints. As a retrospective, single-center observational analysis conducted at a high-volume institution with dedicated expertise in minimally invasive cardiac surgery, the generalizability of the reported outcomes to centers at different stages of TxA-program development warrants careful consideration. The absence of a concurrent control group precludes definitive causal inference and necessitates reliance on indirect comparisons with historical benchmarks. Low absolute event rates, while clinically encouraging, limit the statistical power of multivariable risk models. Specifically, the ratio of outcome events to predictor variables in the multivariable models—10 deaths across three predictors and 30 MACCE events across five predictors—falls below the conventionally recommended threshold of ten events per variable, which may result

in imprecise coefficient estimates and limit the generalizability of the identified risk factors. While this constraint is an inherent consequence of the low perioperative event rates observed—themselves reflecting the safety of the procedure and the stringency of patient selection—the findings of the multivariable analyses should be interpreted with appropriate caution and ideally corroborated in larger pooled datasets. Long-term follow-up data, including prosthesis durability and late clinical outcomes, are not captured within the scope of this analysis and remain an important focus for future investigation.

Conclusions

The present series of 1,848 consecutive patients establishes the TxA concept for MICS-AVR as a mature, reproducible and scalable surgical platform, delivering clinical outcomes that are consistent across an expanded patient spectrum and favorable in comparison with established benchmarks for minimally invasive aortic valve surgery. A 30-day mortality of 0.5% in an unselected all-comers population compares favorably with contemporary registry benchmarks for isolated surgical AVR—including an operative mortality of 1.0–2.5% documented in the German Heart Surgery Report and STS Database analyses (18)—and underscores the safety of TxA MICS-AVR even at institutional scale.

These findings carry significance that extends beyond procedural metrics alone. At a moment when the long-term comparative evidence is progressively tilting in favor of surgical aortic valve replacement for patients with meaningful life expectancy—as underscored by recent Bayesian meta-analyses and high-level expert discourse—the field of cardiac surgery faces both an opportunity and an obligation. The opportunity lies in reasserting the primacy of surgery where the evidence demands it. The obligation is to do so in a form that patients will accept—and increasingly, patients will only accept what they can barely see.

Full median sternotomy, the historical foundation of cardiac surgery, is no longer a neutral proposition in the age of transcatheter therapy. Its visible scar, prolonged recovery and perceived invasiveness impose a competitive disadvantage that clinical outcome data alone cannot overcome, particularly when an alternative exists that is percutaneous in appearance if not in mechanism. The TxA concept bridges this divide. By concealing its access within the natural contours of the lateral chest wall, it offers the cosmetic language of TAVI while delivering the surgical substance and safety patterns of open valve replacement—proven implant durability, complete anatomical correction and the full spectrum of concomitant procedural options.

The TxA concept does not merely represent a new access route. It represents a surgical answer to a cultural shift—and on the evidence presented here, it is an answer that is ready to be heard.

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Footnote

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