

Transaxillary access for ascending aortic and root surgery: a single-center comparison with full and partial sternotomy

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Background: Minimally invasive approaches for ascending aortic and root surgery remain controversial regarding operative complexity and safety. The transaxillary (TAX) approach avoids sternotomy entirely but has not been compared with both full sternotomy (FS) and partial upper sternotomy [minimally invasive cardiac surgery (MIC)]. This study evaluates perioperative outcomes across these three access strategies.

Methods: Between January 2022 and December 2025, 194 consecutive patients undergoing elective isolated ascending aortic or root surgery were retrospectively analyzed. Surgical access was FS (n=52), MIC (n=106), or TAX (n=36). TAX suitability was assessed by team consensus on electrocardiogram (ECG)-gated computed tomography (CT). Primary endpoints were in-hospital mortality, major complications [Society of Thoracic Surgeons (STS) composite], and hospital length of stay. TAX was compared with MIC after 1:2 propensity score matching. FS served as descriptive reference.

Results: FS patients had higher EuroSCORE II (median 2.7 *vs.* MIC 2.2 *vs.* TAX 2.3%, $P=0.006$). Cardiopulmonary bypass time was longer in TAX [196 [interquartile range (IQR): 175–239] *vs.* MIC 160 [138–192] *vs.* FS 172 [140–198] min, $P<0.001$], while cross-clamp time did not differ ($P=0.34$). In-hospital mortality was 3.8% (FS), 0% (MIC), and 0% (TAX). Major complications occurred in 26.9%, 12.3%, and 8.3% ($P=0.02$), and acute kidney injury (AKI) in 28.8%, 8.5%, and 2.8% ($P<0.001$). One stroke occurred in the FS group. In the matched cohort (34 TAX *vs.* 68 MIC), bypass time remained longer in TAX [196 [175–240] *vs.* 160 [139–190] min, $P<0.001$], whereas cross-clamp time, intensive care unit (ICU) and hospital stay, major complications (5.9% *vs.* 11.8%), AKI (2.9% *vs.* 10.3%), atrial fibrillation, and wound complications did not differ significantly.

Conclusions: TAX ascending aortic and root surgery was feasible in carefully selected patients, with no in-hospital mortality, no stroke, and no wound complications. In a propensity-matched comparison with partial upper sternotomy, early outcomes did not differ significantly despite longer bypass time. TAX extends the sternal-sparing concept to the aortic root and ascending aorta and warrants prospective evaluation.

Keywords: Ascending aortic surgery; aortic root replacement; transaxillary (TAX); minimally invasive cardiac surgery (MIC); right anterior mini-thoracotomy (RAMT)



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Introduction

Minimally invasive access is widely accepted for isolated aortic valve replacement, but its extension to ascending aortic and root surgery remains debated. Full median sternotomy remains standard, owing to concerns over exposure, operative complexity, and safety in more extensive procedures.

Partial upper sternotomy has shown that surgical trauma can be reduced without compromising procedural control. Lateral non-sternotomy approaches, particularly right anterior mini-thoracotomy (RAMT) and transaxillary (TAX) access, have further challenged routine sternotomy. For isolated valve surgery, these approaches have been associated with reduced transfusion, recovery, and wound complications (1). Whether these benefits extend to ascending aortic and root procedures is less clear.

Since Prêtre and Turina's first description in 1999 (2), groups have reported non-sternotomy ascending aortic surgery (3-6), but the literature remains predominantly of case series. Comparative studies emerged only recently (7,8). No study has provided a three-way comparison of full sternotomy (FS), partial upper sternotomy, and a lateral non-sternotomy approach across the full spectrum of isolated ascending aortic and root surgery.

This retrospective single-center study compares perioperative outcomes of the TAX approach for isolated ascending aortic and root surgery with those of full and partial upper sternotomy. The comparison with partial upper sternotomy uses propensity-score matching. In addition, the study describes the imaging-based anatomical criteria used to select patients for TAX access.

Methods

This retrospective observational cohort study was conducted at a single tertiary aortic referral center, with data prospectively entered into an institutional database and retrospectively analyzed.

Ethical review

The study was approved by the institutional review board of the Medical Association of Rheinland-Pfalz, Germany (No. 2026-18572) on 3rd February 2026, per the Declaration of Helsinki. Given the retrospective design, informed consent was waived.

Patients

All consecutive adult patients undergoing elective, isolated ascending aortic or root surgery between January 2022 and December 2025 were eligible. Consecutive inclusion was verified by cross-checking institutional operative logs with the prospective surgical database. Procedures were supracoronary ascending aortic replacement (AAR), Wheat, Bentall, and David via FS, partial upper sternotomy [minimally invasive cardiac surgery (MIC)], or TAX access. Exclusion criteria were emergency operations, aortic dissection, aortic arch replacement, and planned concomitant coronary artery bypass grafting (CABG) for known coronary artery disease. The final cohort comprised 194 patients (FS, n=52; MIC, n=106; TAX, n=36).

Primary endpoints were in-hospital mortality, major postoperative complications, and length of hospital stay. Major postoperative complications were defined as a composite according to the Society of Thoracic Surgeons (STS) definition of operative mortality or major morbidity (9): in-hospital death, permanent stroke, renal failure [new dialysis or acute kidney injury (AKI) stage 3], prolonged ventilation exceeding 24 hours, wound healing disturbance, and reoperation for any cause. In deviation from the STS

definition, wound healing disturbances of any depth were counted, because superficial and deep infections were not distinguished in the database, which yields a conservative estimate of the composite. Patients were counted once regardless of the number of events. AKI was defined and staged according to the Kidney Disease: Improving Global Outcomes (KDIGO) serum creatinine criteria (10) using the preoperative baseline value and the peak creatinine within 48 hours and within 7 days after surgery. Stroke was defined as a new focal neurological deficit persisting beyond 24 hours or confirmed by cerebral imaging, and transient ischemic attack (TIA) as a deficit resolving within 24 hours without imaging evidence of infarction. Secondary endpoints were operative times, transfusion requirements, and the individual components of the composite.

Patient selection and preoperative imaging assessment

All elective candidates underwent electrocardiogram (ECG)-gated photon-counting computed tomography (CT) angiography, using a transcatheter-valve-planning protocol, from the thoracic inlet to the femoral bifurcation, including the chest wall to assess thoracic aortic position. TAX suitability was judged, without rigid quantitative cut-offs, by consensus of a team of TAX and non-TAX surgeons from the imaging and the criteria in *Table 1*. The clinical and anatomical configuration was evaluated as a whole.

Table 1 Preoperative imaging-based and clinical assessment used to select patients for the transaxillary approach

Domain	Favors TAX	Argues against TAX (alternative)
Aortic position (level of PA bifurcation)	Right of or centered on sternum; chest-wall-to-valve distance within instrument reach (rarely >15 cm)	Markedly left-displaced heart, e.g., after left pneumonectomy or in severe scoliosis (MIC/FS); pectus excavatum acceptable
Morphology and distal extent	Root-predominant disease; clampable segment proximal to innominate artery; distal ascending <45 mm	≥45 mm or marked caliber change toward arch: open distal anastomosis (MIC with right subclavian ACP); aneurysm >6 cm
Calcification	Clamp and anastomotic zones free of relevant calcification (Chitwood clamp)	Clamp-zone calcification, especially near innominate artery (FS/MIC, covered clamp, right subclavian cannulation)
Coronary anatomy	Normal ostial height and size; no CAD requiring revascularization	Anomalies, especially circumflex from right coronary artery, in root procedures; heavily calcified ostia
Peripheral cannulation	Adequate iliofemoral caliber; limited calcification/kinking; low penetrating-ulcer/thrombus burden	Unsuitable iliofemoral access: liberal use of left subclavian artery (direct or side graft); exclusion only if neither feasible (rare)
Chest wall, pleura, and clinical	No right thoracic surgery/irradiation; no CT signs of adhesions; free left-arm elevation	Previous right thoracic surgery (most frequent exclusion); connective tissue disease (restrictive)

ACP, antegrade cerebral perfusion; CAD, coronary artery disease; CT, computed tomography; FS, full sternotomy; MIC, minimally invasive cardiac surgery; PA, pulmonary artery; TAX, transaxillary.

Aortic position and thoracic anatomy

A rightward or sternum-centered aorta was favorable, though six pericardial stay sutures and left-sided single-lung ventilation with positive end-expiratory pressure rendered exposure achievable in nearly all configurations. The rib-to-valve distance, rarely exceeding 15 cm, had to remain within reach of the long-shafted instruments, which measure approximately 30 cm (Fehling Instruments, Karlstein, Germany). Only a markedly left-displaced heart (e.g., after left pneumonectomy or in severe scoliosis) was

regarded as an anatomical exclusion. Pectus excavatum was not. The target intercostal space was planned by 3Mensio simulation (Pie Medical Imaging, Maastricht, the Netherlands), usually the fourth, occasionally the third or fifth.

Aortic morphology, dimensions, and distal extent

Root-predominant pathology was ideally suited, minimizing retention of diseased aorta distally. Whether the distal aorta needs an open distal anastomosis was a matter of principle, not access. Per the 45-mm threshold (11), a distal ascending or proximal arch diameter ≥ 45 mm, especially with marked caliber change in younger patients, prompted open distal anastomosis via partial or FS with antegrade cerebral perfusion. Otherwise, adequate arch mobilization allowed TAX cross-clamping immediately proximal to the innominate artery, so the distal anastomosis level did not differ between approaches. Aneurysms over approximately 6 cm were not approached transaxillarily, given overview and wall fragility, and rarely offered an adequate clamping zone, usually requiring an open distal anastomosis anyway.

Calcification

In our technique, a standard Chitwood clamp is used to allow clamping sufficiently high and close to the innominate artery. Relevant calcification of the ascending aorta or the peri-innominate segment was therefore a contraindication. These patients underwent full or partial sternotomy with a soft-covered clamp (Applied Medical, Rancho Santa Margarita, CA, USA) and right subclavian cannulation to minimize embolic risk and wash out calcific debris.

Coronary anatomy

Coronary ostial height, vessel size, and anomalies were assessed on the same CT. Coronary artery disease requiring revascularization was excluded, with invasive angiography only when CT suggested stenoses. A restrictive attitude applied to root procedures with coronary anomalies, particularly a circumflex from the right coronary artery, and to heavily calcified ostia.

Peripheral cannulation

The iliofemoral axis and abdominal and descending aorta were assessed for caliber, calcification, kinking, penetrating ulcers, and thrombus load, to minimize retrograde embolization. Because the TAX position elevates the right arm into the field, the right subclavian artery, the usual partial-sternotomy alternative, is inaccessible. The left subclavian was therefore used liberally when iliofemoral vessels were unsuitable or atheroma argued against retrograde femoral perfusion. Vessels precluding both femoral and subclavian cannulation were a rare exclusion.

Clinical criteria

History and examination addressed previous right-sided thoracic surgery or irradiation and the ability to elevate the right arm above the head, as required for positioning. CT was also screened for indirect signs of pleural adhesions, such as old rib fractures, pulmonary scarring, or tumors. Connective tissue disease prompted caution over the distal anastomosis. The most frequent reasons to withhold TAX were previous right thoracic surgery and calcification of the intended clamping zone. Previous cardiac

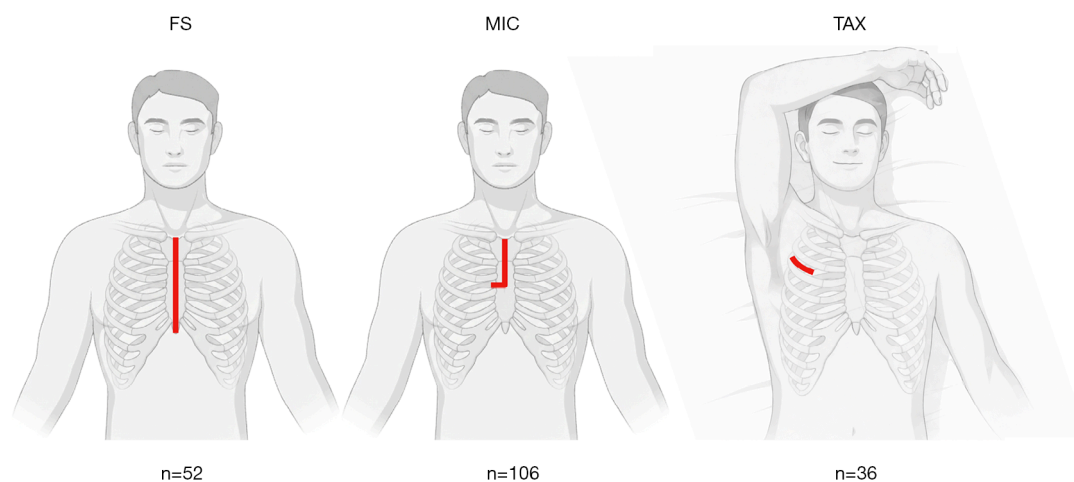


Figure 1 Surgical access routes for isolated ascending aortic and root surgery: FS (n=52), partial upper sternotomy (MIC, n=106), and TAX (n=36). The red line indicates the skin incision. FS, full sternotomy; MIC, minimally invasive cardiac surgery; TAX, transaxillary approach.

surgery was not an absolute contraindication. One patient with prosthetic valve endocarditis after aortic valve replacement and absent sternal continuity following latissimus dorsi flap coverage was deliberately selected for TAX.

Surgical technique

All procedures were performed by attending cardiac surgeons at a single center. Access was chosen at the surgeon's discretion based on anatomy, pathology complexity, and technical feasibility, without a formal allocation protocol. The TAX approach was introduced for ascending aortic and root surgery in September 2023. The three access routes are illustrated in *Figure 1*.

For TAX, the patient is placed in a modified left lateral decubitus position tilted approximately 45° with the right arm elevated. Femoral arterial and venous cannulation is performed percutaneously with two suture-based closure devices (ProGlide, Abbott, Abbott Park, IL, USA). When iliofemoral vessels are unsuitable, the left subclavian artery is used, directly or through a side graft. A 5 cm anterior axillary incision enters the thorax through the planned intercostal space (usually the fourth, occasionally the third or fifth). On cardiopulmonary bypass (CPB), the pericardium is opened, six pericardial stay sutures are retracted toward the minithoracotomy, and left-sided single-lung ventilation with positive end-expiratory pressure displaces the situs. Anastomoses are performed with long-shafted instruments (Fehling Instruments, Karlstein, Germany). After extensive arch mobilization, a Chitwood clamp is applied through the same intercostal space, immediately proximal to the innominate artery when required. The heart is arrested with antegrade cardioplegia and the intended procedure (AAR, Wheat, Bentall, or David) performed under direct vision. During the study period, prophylactic administration of prothrombin complex concentrate (PCC) after protamine was increasingly adopted for lateral thoracotomy access on cardiopulmonary bypass to reduce chest wall bleeding.

For partial upper sternotomy (MIC), a J- or L-shaped partial sternotomy is performed through a 6–10 cm skin incision. Arterial cannulation is via the ascending aorta, right subclavian artery, or femoral artery, with right atrial or femoral venous drainage, and the procedure is performed in standard fashion.

For FS, a complete median sternotomy provides full access to the heart and great vessels, with standard aortic and right atrial cannulation for cardiopulmonary bypass.

Statistical analysis

Group comparisons were performed with IBM SPSS Statistics version 29.0.2.0 (IBM, Armonk, NY, USA) and Wizard Pro version 1.9.7 (Evan Miller, Chicago, IL, USA), propensity score matching and standardized mean differences (SMDs) with Python version 3.12 (SciPy, statsmodels), and figures were prepared with GraphPad Prism version 10.0.0 (GraphPad Software, Boston, MA, USA). Normality of continuous variables was assessed with the Shapiro-Wilk test in each group. Because no continuous variable was normally distributed in all three groups, continuous data were compared with the Kruskal-Wallis test for three groups and the Mann-Whitney U test for two groups, and are presented as median [interquartile range (IQR)]. Transfusion and coagulation products are presented as mean $\pm$ standard deviation (SD), because their median and IQR were zero in all groups and would not convey the differences tested. Times are reported as whole numbers. Categorical data are presented as absolute numbers (percentages) and compared with the Chi-squared test or, when any expected cell count was below 5, Fisher's exact test (Freeman-Halton extension for three groups). Significance was set at alpha 0.05. Significant P values are denoted by asterisks: *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$. Data were complete for all baseline, operative, and outcome variables.

Because access was assigned at the surgeon's discretion, TAX was compared with MIC after propensity score matching. The propensity score was estimated by logistic regression of TAX *vs.* MIC on age, sex, body mass index (BMI), EuroSCORE II, preoperative creatinine levels, and root replacement as a marker of procedural complexity. STS score was not included in addition to EuroSCORE II to avoid collinearity. TAX patients were matched 1:2 to MIC patients by nearest-neighbor matching without replacement within a caliper of 0.2 SDs of the logit of the propensity score (12). Balance was assessed with SMD. The FS group differed substantially in baseline risk and is presented as a descriptive reference without adjusted comparison.

No adjustment for multiple comparisons was made. Beyond the prespecified primary endpoints, all comparisons are exploratory and P values should be interpreted descriptively.

Results

Feasibility

TAX was completed as planned in 35 of 36 patients (97.2%). The single conversion to FS (2.8%) was elective and precautionary: after weaning from cardiopulmonary bypass, minor bleeding at the right coronary ostium, identified during hemostasis, could not be securely controlled via the TAX approach, prompting conversion with hemostasis

achieved without sequelae. No cannulation-related complications occurred in TAX. The left subclavian artery was used in three TAX patients, the femoral artery in all others.

Baseline characteristics

Baseline characteristics are shown in *Table 2*. Sex, age, BMI, aneurysm size, and comorbidities other than chronic obstructive pulmonary disease (COPD) did not differ significantly between groups. FS patients had a higher risk profile, with higher STS scores [1.7% (0.9–2.2)% *vs.* MIC 0.8% (0.6–1.1)% *vs.* TAX 0.7% (0.6–1.1)%; $P<0.001$], EuroSCORE II [2.7% (2.0–3.9)% *vs.* 2.2% (1.8–2.7)% *vs.* 2.3% (1.8–3.2)%; $P=0.006$], and COPD prevalence (11.5% *vs.* 1.9% *vs.* 2.8%; $P=0.03$).

Operative details

Operative details are summarized in *Table 3* and the distribution of procedures in *Figure 2*. Bentall (FS 36.5%, MIC 22.6%, TAX 36.1%; $P=0.11$) and David procedures (FS 15.4%, MIC 19.8%, TAX 16.7%; $P=0.77$) were distributed similarly across groups. Concomitant Maze procedures (FS 13.5%, MIC 0.9%, TAX 5.6%; $P=0.002$) and left atrial appendage closure (21.2%, 4.7%, 5.6%; $P=0.004$) were more frequent in FS.

Cardiopulmonary bypass time was longer in TAX {196 [175–239] min} than in MIC {160 [138–192] min} and FS {172 [140–198] min, $P<0.001$ }, whereas cross-clamp time did not differ {TAX, 132 [107–162] min; MIC, 120 [105–148] min; FS, 132 [101–152] min; $P=0.34$ }. Skin-to-skin time was 300 [260–334] min in TAX *vs.* 272 [240–300] min in MIC and 270 [240–300] min in FS ($P=0.06$). The lowest core temperature during bypass was similar ($P=0.24$). Cannulation complications were rare (FS 1.9%, MIC 0.9%, TAX 0%; $P=0.70$).

Transfusion

Transfusion requirements are shown in *Table 3*. FS required more red blood cell (0.9 ± 1.7 *vs.* MIC 0.3 ± 1.0 *vs.* TAX 0.4 ± 0.8 units, $P=0.03$) and platelet transfusions (0.5 ± 0.9 *vs.* 0.2 ± 0.7 *vs.* 0.2 ± 0.6 units, $P=0.03$). Fresh frozen plasma, fibrinogen, and PCC did not differ between the three groups, but PCC was given more often in TAX than in MIC (any PCC 44.4% *vs.* 20.8%; 489 ± 720 *vs.* $440\pm1,022$ IU, $P=0.03$), reflecting the prophylactic use for lateral access described above rather than increased bleeding, as red blood cell use and rethoracotomy rates were not increased in TAX.

Postoperative outcomes

Postoperative outcomes are shown in *Table 4*. Two in-hospital deaths occurred, both in FS (3.8%), with no deaths in MIC and TAX ($P=0.10$). Major complications occurred in 26.9% of FS, 12.3% of MIC, and 8.3% of TAX patients ($P=0.02$). Intensive care unit (ICU) stay {26 [20–72] *vs.* 21 [18–27] *vs.* 24 [9–52] h, $P=0.007$ }, time to extubation {6 [4–9] *vs.* 4 [3–6] *vs.* 4 [3–6] h, $P=0.003$ }, and hospital stay {12 [9–16] *vs.* 9 [8–12] *vs.* 9 [8–13] days; $P=0.003$ } were longest in FS.

Table 2 Baseline characteristics of 194 patients undergoing isolated ascending aortic and root surgery, stratified by surgical access

Variable	FS (n=52)	MIC (n=106)	TAX (n=36)	P
Male	37 (71.2)	75 (70.8)	24 (66.7)	0.88
Age (years)	63.5 [58.4–72.6]	61.5 [56.0–68.9]	60.5 [53.0–70.2]	0.12
BMI (kg/m ²)	28.1 [25.3–31.4]	27.1 [24.4–30.8]	26.5 [24.4–30.2]	0.52
STS score (%)	1.7 [0.9–2.2]	0.8 [0.6–1.1]	0.7 [0.6–1.1]	<0.001***
EuroSCORE II (%)	2.7 [2.0–3.9]	2.2 [1.8–2.7]	2.3 [1.8–3.2]	0.006**
Preop. creatinine (mg/dL)	1.0 [0.8–1.2]	0.9 [0.8–1.1]	0.9 [0.8–1.1]	0.19
Aneurysm size (cm)	5.1 [4.9–5.5]	5.0 [4.8–5.4]	5.0 [4.7–5.2]	0.16
Hypertension	35 (67.3)	52 (49.1)	18 (50.0)	0.08
Diabetes mellitus	6 (11.5)	4 (3.8)	3 (8.3)	0.14
Smoking	12 (23.1)	17 (16.0)	7 (19.4)	0.56
Coronary artery disease	4 (7.7)	8 (7.5)	1 (2.8)	0.74
COPD	6 (11.5)	2 (1.9)	1 (2.8)	0.03*
Hyperlipidemia	10 (19.2)	24 (22.6)	7 (19.4)	0.85
Renal insufficiency	7 (13.5)	4 (3.8)	2 (5.6)	0.07
Previous cardiac surgery	0 (0.0)	5 (4.7)	1 (2.8)	0.27

Continuous data are median [interquartile range], categorical data n (%). *, P<0.05; **, P<0.01; ***, P<0.001. BMI, body mass index; COPD, chronic obstructive pulmonary disease; FS, full sternotomy; MIC, minimally invasive cardiac surgery; STS, Society of Thoracic Surgeons; TAX, transaxillary.

Table 3 Operative details and transfusion requirements

Variable	FS (n=52)	MIC (n=106)	TAX (n=36)	P
Wheat	18 (34.6)	51 (48.1)	15 (41.7)	0.27
Bentall	19 (36.5)	24 (22.6)	13 (36.1)	0.11
David	8 (15.4)	21 (19.8)	6 (16.7)	0.77
AAR	7 (13.5)	10 (9.4)	2 (5.6)	0.49
Root replacement	28 (53.8)	46 (43.4)	19 (52.8)	0.38
Aortic valve replacement	37 (71.2)	77 (72.6)	28 (77.8)	0.77
CABG (unplanned)	1 (1.9)	1 (0.9)	1 (2.8)	0.59
Maze	7 (13.5)	1 (0.9)	2 (5.6)	0.002**
LAA closure	11 (21.2)	5 (4.7)	2 (5.6)	0.004**
Conversion to FS	0 (0.0)	0 (0.0)	1 (2.8)	0.19

Table 3 (continued)

Variable	FS (n=52)	MIC (n=106)	TAX (n=36)	P
CPB time (min)	172 [140–198]	160 [138–192]	196 [175–239]	<0.001***
Cross-clamp time (min)	132 [101–152]	120 [105–148]	132 [107–162]	0.34
Skin-to-skin time (min)	270 [240–300]	272 [240–300]	300 [260–334]	0.06
Lowest temperature (°C)	32.2 [32.0–33.7]	32.3 [32.0–33.9]	32.2 [32.0–32.5]	0.24
Cannulation complication	1 (1.9)	1 (0.9)	0 (0.0)	0.70
RBC (units)	0.9±1.7	0.3±1.0	0.4±0.8	0.03*
Platelets (units)	0.5±0.9	0.2±0.7	0.2±0.6	0.03*
FFP (units)	0.4±1.4	0.1±0.6	0.2±0.7	0.09
PCC (IU)	581±1106	440±1022	489±720	0.11
Fibrinogen (g)	0.8±1.5	0.8±1.3	0.6±1.2	0.92

Continuous data are median [interquartile range]; transfusion and coagulation products are mean ± standard deviation; categorical data n (%). *, P<0.05; **, P<0.01; ***, P<0.001. AAR, supracoronary ascending aortic replacement; CABG, coronary artery bypass grafting; CPB, cardiopulmonary bypass; FFP, fresh frozen plasma; FS, full sternotomy; LAA, left atrial appendage; MIC, minimally invasive cardiac surgery; PCC, prothrombin complex concentrate; RBC, red blood cell; TAX, transaxillary.

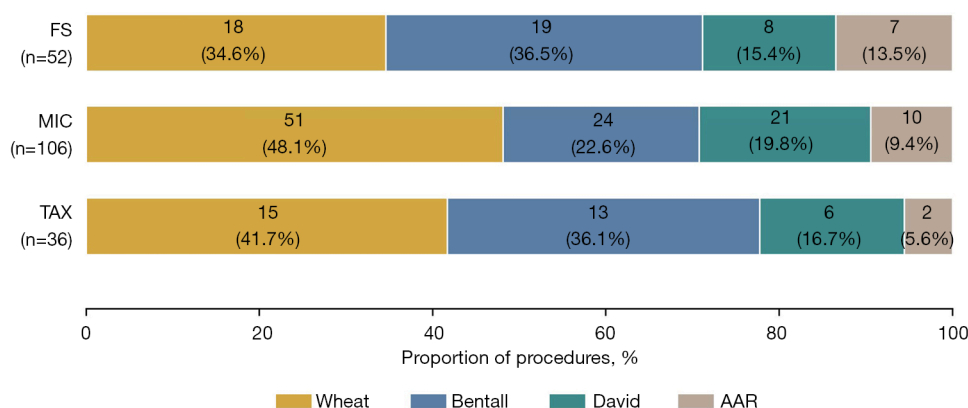


Figure 2 Distribution of surgical procedures stratified by surgical access. Stacked bar chart showing the number and proportion of Wheat, Bentall, David, and supracoronary AAR procedures in each group. The procedural spectrum did not differ significantly between the three approaches. AAR, ascending aortic replacement; FS, full sternotomy; MIC, minimally invasive cardiac surgery; TAX, transaxillary approach.

Rethoracotomy occurred in 13.5% (FS), 7.5% (MIC), and 5.6% (TAX) ($P=0.40$), and new-onset atrial fibrillation in 38.5%, 38.7%, and 22.2% ($P=0.18$). No wound healing disturbance occurred in TAX, *vs.* 3.8% in MIC and 7.7% in FS ($P=0.25$). New dialysis ($P=0.007$), tracheotomy, and extracorporeal life support (ECLS) (each $P=0.02$) occurred almost exclusively in FS. Prolonged ventilation beyond 24 hours occurred in 7.7% (FS), 0.9% (MIC), and 5.6% (TAX) ($P=0.06$). One stroke occurred, in an FS patient (1.9%), and no TIA in any group. AKI of any KDIGO stage occurred in 28.8%, 8.5%, and 2.8% ($P<0.001$), and stage 3 in 13.5%, 0.9%, and 0.0% ($P=0.002$). Descriptively, TAX had the lowest rates of major complications, AKI, atrial fibrillation, and wound

Table 4 Postoperative outcomes

Variable	FS (n=52)	MIC (n=106)	TAX (n=36)	P
ICU stay (h)	26 [20–72]	21 [18–27]	24 [19–52]	0.007**
Time to extubation (h)	6 [4–9]	4 [3–6]	4 [3–6]	0.003**
Hospital stay (days)	12 [9–16]	9 [8–12]	9 [8–13]	0.003**
In-hospital mortality	2 (3.8)	0 (0.0)	0 (0.0)	0.10
Major complications (STS composite)	14 (26.9)	13 (12.3)	3 (8.3)	0.02*
Stroke	1 (1.9)	0 (0.0)	0 (0.0)	0.45
TIA	0 (0.0)	0 (0.0)	0 (0.0)	N.A.
AKI, any (KDIGO stage 1–3)	15 (28.8)	9 (8.5)	1 (2.8)	<0.001***
AKI stage 1	8 (15.4)	7 (6.6)	1 (2.8)	0.09
AKI stage 2	0 (0.0)	1 (0.9)	0 (0.0)	>0.99
AKI stage 3	7 (13.5)	1 (0.9)	0 (0.0)	0.002**
Rethoracotomy	7 (13.5)	8 (7.5)	2 (5.6)	0.40
New dialysis	6 (11.5)	1 (0.9)	0 (0.0)	0.007**
Prolonged ventilation >24 h	4 (7.7)	1 (0.9)	2 (5.6)	0.06
Wound healing disturbance	4 (7.7)	4 (3.8)	0 (0.0)	0.25
New-onset atrial fibrillation	20 (38.5)	41 (38.7)	8 (22.2)	0.18
Reintubation	1 (1.9)	2 (1.9)	2 (5.6)	0.48
Tracheotomy	3 (5.8)	0 (0.0)	0 (0.0)	0.02*
ECLS	3 (5.8)	0 (0.0)	0 (0.0)	0.02*
Temporary dialysis	3 (5.8)	0 (0.0)	0 (0.0)	0.02*
Permanent dialysis	3 (5.8)	1 (0.9)	0 (0.0)	0.10
Myocardial infarction	0 (0.0)	1 (0.9)	0 (0.0)	>0.99
HFNV/NIV	3 (5.8)	5 (4.7)	3 (8.3)	0.59
Sepsis	1 (1.9)	0 (0.0)	0 (0.0)	0.45

Continuous data are median [interquartile range], categorical data n (%). *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$. Major complications are the STS composite of in-hospital death, stroke, new dialysis or KDIGO stage 3 acute kidney injury, ventilation >24 hours, wound healing disturbance of any depth, and reoperation. AKI, acute kidney injury; ECLS, extracorporeal life support; FS, full sternotomy; HFNV/NIV, high-flow nasal or non-invasive ventilation; ICU, intensive care unit; KDIGO, Kidney Disease: Improving Global Outcomes; MIC, minimally invasive cardiac surgery; N.A., not applicable (no events in either group); STS, Society of Thoracic Surgeons; TAX, transaxillary; TIA, transient ischemic attack.

healing disturbance of the three groups, and no TAX patient died or sustained a stroke or required ECLS, dialysis, or tracheotomy.

Propensity-matched comparison: TAX vs. MIC

Of 36 TAX patients, 34 were matched to 68 MIC patients. Two TAX patients with markedly elevated preoperative creatinine (3.54 and 2.05 mg/dL) had no MIC patient within the caliper and were excluded from the matched analysis. After matching, SMDs were below 0.2 for all model covariates except preoperative creatinine (0.30, lower in TAX after exclusion of the two unmatched patients) (Table S1). Matched outcomes are

shown in *Table 5* and, side by side with the unadjusted TAX *vs.* MIC comparison, in *Tables S2,S3*.

Cardiopulmonary bypass time remained longer in TAX {196 [175–240] *vs.* 160 [139–190] min, $P<0.001$ }, as did skin-to-skin time {300 [260–330] *vs.* 275 [240–301] min, $P=0.02$ }, whereas cross-clamp time did not differ {132 [109–168] *vs.* 120 [106–149] min, $P=0.16$ }. There were no in-hospital deaths and no strokes in either matched group. Major complications (5.9% *vs.* 11.8%, $P=0.49$), AKI (2.9% *vs.* 10.3%, $P=0.26$), ICU stay ($P=0.53$), time to extubation ($P=0.27$), hospital stay ($P=0.52$), rethoracotomy ($P>0.99$), new-onset atrial fibrillation (23.5% *vs.* 38.2%, $P=0.18$), and wound healing disturbance (0.0% *vs.* 2.9%, $P=0.55$) did not differ significantly. PCC use remained higher in TAX (515±733 *vs.* 321±731 IU, $P=0.02$) without a difference in red blood cell transfusion.

Table 5 Outcomes after 1:2 propensity score matching, TAX (n=34) *vs.* MIC (n=68)

Variable	TAX (n=34)	MIC (n=68)	P
CPB time (min)	196 [175–240]	160 [139–190]	<0.001***
Cross-clamp time (min)	132 [109–168]	120 [106–149]	0.16
Skin-to-skin time (min)	300 [260–330]	275 [240–301]	0.02*
RBC (units)	0.3±0.7	0.4±1.1	0.57
PCC (IU)	515±733	321±731	0.02*
ICU stay (hours)	22 [18–42]	21 [18–27]	0.53
Time to extubation (hours)	4 [3–6]	4 [3–6]	0.27
Hospital stay (days)	9 [8–13]	9 [8–12]	0.52
In-hospital mortality	0 (0.0)	0 (0.0)	N.A.
Major complications (STS composite)	2 (5.9)	8 (11.8)	0.49
Stroke	0 (0.0)	0 (0.0)	N.A.
TIA	0 (0.0)	0 (0.0)	N.A.
AKI, any (KDIGO stage 1–3)	1 (2.9)	7 (10.3)	0.26
AKI stage 1	1 (2.9)	5 (7.4)	0.66
AKI stage 2	0 (0.0)	1 (1.5)	>0.99
AKI stage 3	0 (0.0)	1 (1.5)	>0.99
Rethoracotomy	2 (5.9)	5 (7.4)	>0.99
New dialysis	0 (0.0)	1 (1.5)	>0.99
Prolonged ventilation >24 h	1 (2.9)	1 (1.5)	>0.99
Wound healing disturbance	0 (0.0)	2 (2.9)	0.55
New-onset atrial fibrillation	8 (23.5)	26 (38.2)	0.18
Reintubation	1 (2.9)	2 (2.9)	>0.99
HFNV/NIV	3 (8.8)	3 (4.4)	0.40

Continuous data are median [interquartile range]; transfusion and coagulation products are mean ± standard deviation; categorical data n (%). *, $P<0.05$; ***, $P<0.001$. AKI, acute kidney injury; CPB, cardiopulmonary bypass; HFNV/NIV, high-flow nasal or non-invasive ventilation; ICU, intensive care unit; KDIGO, Kidney Disease: Improving Global Outcomes; MIC, minimally invasive cardiac surgery; N.A., not applicable (no events in either group); PCC, prothrombin complex concentrate; RBC, red blood cell; STS, Society of Thoracic Surgeons; TAX, transaxillary; TIA, transient ischemic attack.

Discussion

This study is the first three-way comparison of TAX, partial upper sternotomy, and FS for isolated ascending aortic and root surgery, and the first propensity-matched comparison of TAX with partial upper sternotomy. In the matched analysis, early clinical outcomes did not differ despite longer cardiopulmonary bypass times, and no TAX patient died or sustained a stroke or a wound complication. The FS group represented a higher-risk population and serves as a descriptive reference.

The TAX results are inseparable from anatomical selection. In right-sided minimally invasive valve surgery, established CT criteria include the intercostal-space-to-valve distance within instrument reach (13), and the TAX route has reached valve replacement with ultra-fast-track recovery (14). For direct-view ascending and root surgery, the aorta's position relative to the sternum remained a useful orientation, but because pericardial traction and single-lung ventilation render exposure achievable in nearly all configurations, the decisive criteria were the clamping and anastomotic zones, distal pathology extent, and retrograde-perfusion safety.

The distal extent of aortic treatment must not be dictated by access. Patients anticipated to need an open distal anastomosis because of a distal diameter ≥ 45 mm (11) or a marked caliber change toward the arch in younger patients were deliberately treated via partial or FS with antegrade cerebral perfusion rather than via the TAX approach. Defining this boundary preoperatively keeps TAX within its safety envelope and, by avoiding retained diseased aorta, is a prerequisite both for durable long-term results and for reproducing the outcomes reported here.

Median CPB time was about 35 minutes longer for TAX than for partial sternotomy, in the unmatched and the matched comparison, and about 25 minutes longer than for FS, yet cross-clamp times did not differ. This is clinically relevant, since myocardial ischemia time more critically determines cardiac morbidity. The longer CPB reflects steps performed on bypass before cross-clamping, namely opening the pericardium, dissecting the ascending aorta, and identifying the clamp site, which in sternotomy precede CPB. CPB duration has been linked to AKI (15), but despite the longer bypass times, KDIGO-defined AKI occurred in only one TAX patient (2.8%) and did not differ from MIC in the matched comparison. Longer CPB with similar clamp times and no excess morbidity has likewise been reported for RAMT aortic surgery (7,8,16). In the matched comparison, neither time to extubation {4 [3–6] *vs.* 4 [3–6] h} nor prolonged ventilation beyond 24 hours (2.9% *vs.* 1.5%) differed between TAX and MIC.

The lower rate of new-onset atrial fibrillation in TAX (22.2% *vs.* 38.7% for MIC and 38.5% for FS) was not significant in the unmatched or the matched comparison and is hypothesis-generating. It aligns with reports from minimally invasive aortic valve surgery, where right anterior thoracotomy is associated with less new-onset atrial fibrillation than sternotomy (17,18), possibly reflecting reduced pericardial manipulation.

No wound healing disturbance occurred in TAX, *vs.* 3.8% in MIC and 7.7% in FS. Although not statistically significant, avoidance of sternal wound complications is a structural feature of the non-sternotomy approach (7,8,16,19), particularly relevant with diabetes, obesity, or immunosuppression.

The FS group had higher risk scores and COPD prevalence and more frequent concomitant Maze and left atrial appendage procedures, reflecting that patients

too complex for minimally invasive approaches undergo FS. The excess of ECLS, tracheotomy, and dialysis in FS is best explained by this risk profile and does not permit conclusions about the access itself. FS is therefore presented as a descriptive reference, and the propensity-matched comparison with MIC is the meaningful benchmark for TAX. Without formal comparison to FS, it remains a factual observation of this cohort that TAX had the lowest rates of major complications, AKI, atrial fibrillation, and wound complications of the three approaches, and that no stroke occurred despite predominantly femoral cannulation.

Aortic replacement was indicated per the 2024 European Association for Cardio-Thoracic Surgery (EACTS)/STS aortic guidelines (11). Owing to lower thresholds, especially with concomitant procedures, aneurysm size here is somewhat smaller than in earlier studies (7).

Our cohort includes the broadest procedural spectrum reported for a non-sternotomy approach (AAR, Wheat, Bentall, and David). While Bentall via RAMT is reported (5,8,19,20), the David procedure in a TAX cohort has, to our knowledge, not been reported. Case series have confirmed feasibility of complex non-sternotomy aortic procedures (3-6,19-25), and the two comparative studies to date, Durdu *et al.* (7) and Zhao *et al.* (8), reported shorter stays without a safety penalty despite longer operative times.

Finally, where partial upper sternotomy is accepted, TAX may be a reasonable sternal-sparing alternative in anatomically suitable patients. Preserving sternal integrity obviates sternal precautions and permits unrestricted early upper-body mobilization, making TAX a candidate for enhanced recovery after surgery (ERAS) pathways (26), building on early reports of ultra-fast-track TAX valve surgery (14). These potential advantages warrant prospective evaluation.

Limitations

This study is limited by its retrospective, single-center design and the small TAX cohort (n=36). Access was assigned at the surgeon's discretion, and TAX eligibility was determined by a qualitative, imaging-based team assessment without systematic quantitative CT measurements or a screening log, so selection rates cannot be quantified. Propensity score matching can only account for measured covariates. Residual selection bias by anatomical suitability therefore cannot be excluded and may favor the TAX group. The FS group differed substantially in baseline risk and was not adjusted.

The study was not powered to detect differences in rare outcomes such as mortality or stroke, and non-significant results should not be read as equivalence. Without correction for multiple comparisons, individual significant findings may be due to chance. TAX was introduced in September 2023, so the cohort includes the learning-curve period.

Conclusions

In carefully selected patients, the TAX approach for isolated ascending aortic and root surgery was feasible across a broad spectrum including supracoronary replacement, Wheat, Bentall, and David procedures, with no in-hospital mortality, no stroke, and

no wound complications. These results rest on preoperative CT assessment of aortic morphology, position, calcification, coronary anatomy, and peripheral access, with an access-independent decision on the distal extent of repair. In propensity-matched comparison with partial upper sternotomy, cardiopulmonary bypass times were longer, cross-clamp times did not differ, and early clinical outcomes did not differ significantly. Where partial sternotomy is accepted, TAX extends the sternal-sparing concept to the aortic root and ascending aorta in anatomically suitable patients, with potential advantages for postoperative recovery that warrant prospective evaluation.

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Footnote

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Conflicts of Interest: D.S.D. is a consultant to Artivion Inc. (Kennesaw, GA, USA) and Edwards Lifesciences (Irvine, CA, USA) during the study period. The other authors have no conflicts of interest to declare.

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