Tailored surgical strategies for mini-access open total arch repair

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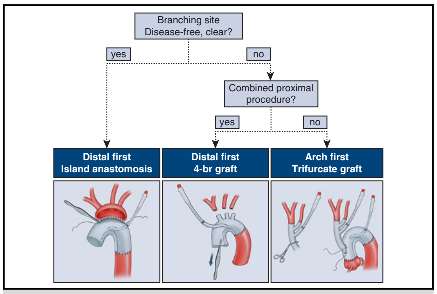
ABSTRACT

Objective: Open arch repair is perceived as a challenging, high-risk procedure, with a barrier against the use of a minimally invasive approach. We aimed to present a mini-access total arch replacement performed by stratified approaches and to evaluate perioperative outcomes to contribute to the body of evidence.

Methods: We evaluated 40 consecutive patients (aged 69.5 years; interquartile range, 65.6-76.3 years) undergoing elective total arch replacement using 5- to 8-cm upper mini-sternotomy between 2018 and 2022. Surgical strategies, including arterial inflow site and methods of branching vessel reconstruction, were systematically selected at the individual level. To evaluate comparative outcomes, contemporary cases undergoing total arch replacement via sternotomy with similar eligibility criteria served as a control group, and the inverse-treatment-weighting method was used to adjust for baseline characteristics.

Results: Arch-first anastomosis using trifurcate graft, distal-first anastomosis using 4-branch graft, and island anastomosis were used in 18 (45%), 12 (30.0%), and 10 (25%) patients, respectively. Lower body and cardiac ischemic times were 23.4 minutes (interquartile range, 18.0-29.0 minutes) and 66.7 minutes (interquartile range, 50.1-78.2 minutes). There was no early (30-day or in-hospital) mortality, and 2 patients experienced disabling stroke (5.0%). The contemporary control group comprised 55 patients. After an adjustment, a mini-access group showed lower risks of stroke (odds ratio, 0.88; 95% CI, 0.78-1.00; $P = .049$) and a composite of major complications (odds ratio, 0.79; 95% CI, 0.68-0.92; $P = .003$), compared with a sternotomy approach.

Conclusions: Based on present results, mini-access total arch replacement may be performed with reasonable safety and efficiency. (JTCVS Techniques 2024;24:1-13)



Decision-making tree for arch vessel anastomosis via ministernotomy.

CENTRAL MESSAGE

With a systematic surgical approach tailored for individual patients, total arch replacement can be performed using mini-sternotomy with reasonable efficiency and safety.

PERSPECTIVE

With a systematic approach tailored for individual patients, total arch replacement can be performed using mini-sternotomy with reasonable efficiency and safety. Compared with the conventional sternotomy approach, mini-sternotomy surgery was associated with more favorable early outcomes, suggesting that this technique may be a viable alternative in the treatment of aortic arch aneurysm.

▶ Video clip is available online.

The surgical management of aortic arch pathologies is undergoing development in response to advancements in supra-aortic trunk reimplantation[1] and arch distal anastomosis using the invagination technique[2] and elephant trunk implantation.[3] Furthermore, not only cerebral protection strategy,[4,5] such as selective cerebral perfusion, were driving factors for mitigating complications and minimizing the risks of developing adverse outcomes but also perioperative care. Despite these efforts, reports continue to indicate mortality and stroke rates of approximately 10%, with no significant improvement observed in recent years.[6] To circumvent

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Abbreviations and Acronyms
CPB = cardiopulmonary bypass
IPTW = inverse probability treatment weighting
SMD = standardized mean difference
TAR = total arch replacement

such complications associated with open surgery, hybrid arch repair procedures, which involve a combination of open debranching of arch vessels and endovascular grafting, have been proposed.[7,8] However, to date, large-scale studies have shown higher risks of developing major adverse events, such as 30-day mortality, stroke, and paraplegia, among a hybrid group compared to a traditional surgical treatment group in patients undergoing total arch replacement (TAR) for zone 0 and 1 equivalent arch aneurysm. This indicates that an open surgical approach is still the gold standard therapy in extensive lesions.[9-11]

Therefore, procedural complexity and the burden of surgical risks seem to not allow minimally invasive cardiac surgery, which is expanding its role in heart valve surgeries. However, several groups have reported promising early outcomes for mini-access surgeries in the treatment of thoracic aortic pathologies, mainly focusing on ascending and hemiarch replacements,[12] while including TAR in small subsets of cases.[13]

In recent years, we have adopted a systematic surgical approach tailored for individual patients to perform TAR using mini-sternotomy to enhance the quality of care. Herein, we present the clinical results of mini-access TAR and aimed to evaluate the comparative effectiveness of mini-access TAR with that of the sternotomy approach.

METHODS

Study Population and Clinical End Points

This study enrolled consecutive patients undergoing elective TAR using upper mini-sternotomy between December 2018, at which we began to perform the mini-access TAR, and June 2022 in the Asan Medical Center, Seoul, Korea, which is a large-volume tertiary referral center. Emergency surgery, redo surgery, and concomitant procedures other than aortic valve surgery and ablation have precluded this mini-access TAR, which was performed by a single surgeon (J.B.K.) during the study period. To evaluate the comparative outcomes of a mini-access group versus conventional full-sternotomy approaches, we identified patients undergoing elective TAR using full sternotomy during the same period with similar eligibility criteria (control group). Four (7.2%) and 11 (20.0%) patients undergoing ablation and aortic valve surgery (with or without root surgery), respectively, were included as concomitant surgery during TAR in the control group. The primary outcome of interest, occurring in the early postoperative period (in-hospital or within 30 days), was death and disabling neurological damage, the latter being diagnosed by an attending neurologist with the aid of an adequate imaging modality, which was defined as disabling if the neurologic damage did not resolve during hospitalization. The primary composite end point was defined to include both early mortality and transient stroke with self-resolving symptoms. Secondary outcomes included individual components of the primary end point, any neurological injury, a requirement for de novo dialysis, cardiogenic shock requiring mechanical support, surgical bleeding requiring re-exploration, vascular-access complication requiring intervention, end-organ failure (ie, mesenteric ischemia) either fatal or requiring intervention, respiratory complication requiring extracorporeal membrane oxygenation, and graft infection. In the interest of capturing patient-side quality measures, we also evaluated the length of hospital stay and postoperative numerical rating scale for surgical pain during hospitalization. The study protocol was approved by the Institutional Review Board of the Asan Medical Center (2023-0412; date of approval: April 6, 2023). Informed consent from individual patients was waived due to the retrospective nature of the study.

Surgical Strategy

Either an upper partial *J*-shaped or an *L*-shaped sternotomy approach was used down to the third or fourth intercostal space with a 5- to 8-cm skin incision. Moderate hypothermic circulatory arrest at target nasopharyngeal temperature of 25 to 28 °C was the default strategy for all the patients. For myocardial protection, 1 L antegrade del Nido cardioplegic solution was administered under aortic clamping, either via root or directly to the coronary ostia, depending on the presence of aortic insufficiency. Arterial cannulation sites for cardiopulmonary bypass (CPB) were individualized, according to the location and character of the aneurysm, with the innominate artery being preferred, as previously described in our study.[14] To facilitate effective distal anastomosis in a limited surgical field, an inverted graft technique was utilized whenever feasible, as previously suggested.[15] This entailed rolling the graft itself in an inside-out fashion, which allows excellent exposure of the distal anastomosis site without hindrance by the graft body. The distal anastomosis was performed using a double layer 3–0 polypropylene suture on the proximal descending aorta. When a secondary descending aortic procedure was deemed necessary, we left the graft end in place and rolled it to create an elephant trunk, followed by suturing (Figure 1). In regard to the method of anastomosing the distal parts and order of head vessel anastomosis, a decision-making tree was utilized for efficiency-oriented surgical flows, as depicted in Figure 2. First, in the absence of connective tissue disorder and with disease-free greater curvature in the arch (either aneurysm or atherosclerosis), an island aortic cuff technique was preferred to simplify head vessel

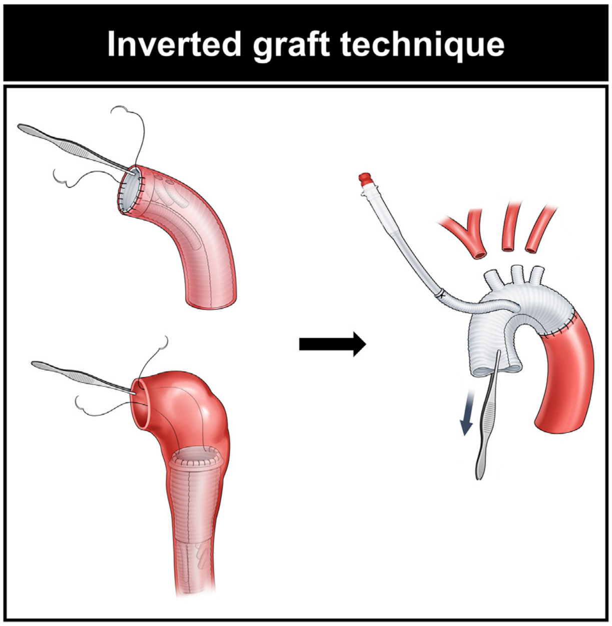


FIGURE 1. Surgical technique of inverted graft used for total arch replacement.

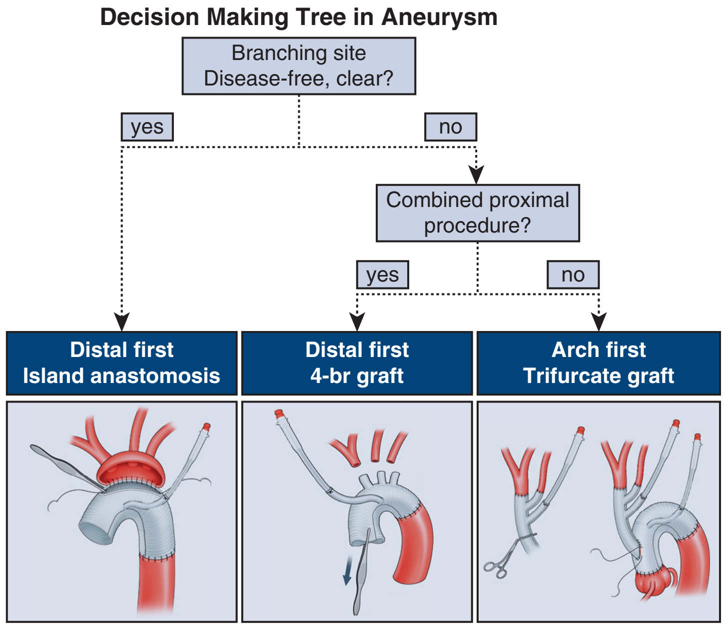
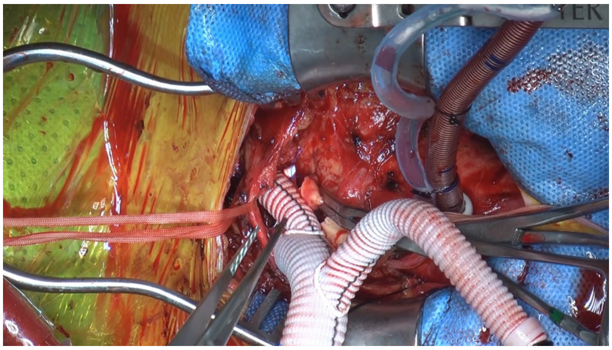


FIGURE 2. Decision-making tree for head vessel anastomosis. *br*, Branch.

anastomosis following distal anastomosis. Second, in cases where combined proximal cardiac procedures were needed, such cardiac procedures were first conducted during hypothermic induction, whereby sufficient time was overlapped to get to the target temperature for circulatory arrest. A commercially available arch 4-branched graft was then used, having distal anastomosis first with the inverted grafting technique, after which systemic perfusion was resumed using the side branch of the graft while raising the temperature. This is serially followed by left common carotid artery revascularization, proximal aortic anastomosis, release of the aortic clamping, and innominate artery revascularization under a beating heart. The left subclavian artery usually gets reattached after weaning from a CPB. This sequence is supposed to have the earliest restoration of bilateral cerebral perfusion, the shortest cardiac ischemic time, and minimal time-redundancy in the management of temperature. Third, if only the TAR was performed, the arch-first technique would be chosen using a trifurcate graft as the first step under CPB support, while lowering the body temperature. For this reason, the innominate artery was first debranched with a short innominate artery clamping time (<5 minutes) during hypothermic induction, after which the perfusion to the innominate artery was resumed by a side branch of the trifurcate graft. This was followed by left common carotid artery debranching, in which the nasopharyngeal temperature comes near the target level. The open distal anastomosis was performed under low body ischemia following cardioplegic arrest of the heart using an inverted graft technique. As soon as the distal anastomosis was completed, whole-body perfusion was resumed through the side branch of the 1-branch graft, which started normalizing the body temperature. The proximal anastomosis was then made, and the aortic clamping was released, which was followed by the graft-to-graft anastomosis between the main aortic and trifurcate grafts. Finally, the left subclavian artery was revascularized after CPB weaning (Video 1).

Data Analysis

Categorical variables were compared using the χ^2 test or Fisher exact test and were reported as frequencies and percentages. The normality of continuous variables was assessed using the Shapiro-Wilk test. For



VIDEO 1. This case was a total arch replacement for rapid expansion of arch aneurysm size because of type III endoleak for thoracic endovascular repair (TEVAR) graft, which was an implanted TEVAR for arch aneurysm in May 2019. The arch first technique was chosen using a trifurcate graft, under the support of cardiopulmonary bypass using ascending aorta and femoral vein while lowering the body temperature. For this, an innominate artery was debranched during hypothermic induction, after which the perfusion to the innominate artery was resumed by a side branch of the trifurcate graft. This was followed by left common carotid artery debranching, at which the nasopharyngeal temperature nears the target level. Open distal anastomosis was performed under low body ischemia following cardioplegic arrest of the heart using an inverted graft technique. After distal anastomosis was completed, whole body perfusion was resumed through the side branch of the 1-branch graft, and we started to normalize the body temperature. Proximal anastomosis was then completed, and aortic clamping was released, which was followed by the graft-to-graft anastomosis between the main aortic and trifurcate grafts. Finally, the left subclavian artery was revascularized usually after the cardiopulmonary bypass weaning. Video available at: https://www.jtcvs.org/article/S2666-2507(23)00478-9/fulltext.

normally distributed variables, the Student *t* test was used, and the results were presented as mean (SD). Nonnormally distributed variables were analyzed using the Kruskal-Wallis test, and the median value and interquartile range (IQR) were reported. To mitigate potential treatment selection bias, the study employed the inverse-probability treatment weighting (IPTW) method based on propensity score modeling. The propensity score was generated at an individual patient level, with the use of a logistic regression model incorporating all preoperative variables available. Each of the patients was weighted using a 1/propensity score and 1/(1-propensity score) in the mini-access and control groups, respectively, to yield an inverse-probability weighted cohort. Finally, we used trimmed stabilized weights with robust SEs. Balancing in baseline variables between the groups was tested by examining standardized mean differences (SMDs), and SMDs <20% were regarded as adequately balanced. Following an adjustment using the IPTW, we employed both logistic regression models to compare the risks of prespecified clinical endpoints between the mini-access and sternotomy TAR groups. Whole variables used in IPTW mating were used in univariable logistic regression and stepwise selection for selecting variables in multiple regression analysis was performed. All reported *P* values were 2-tailed. Statistical analyses were performed using R software, version 4.2.1 (R Foundation for Statistical Computing).

RESULTS

Baseline Characteristics

The study population included 40 patients with a median age of 69.5 years (IQR, 65.5-76.3 years), of whom 32 (80%) were men. Baseline demographic characteristics and clinical profiles presenting pathology of the aortic arch are shown in Table 1. Degenerative aneurysm was identified as the predominant pathology, accounting for the majority (n = 29 [72.5%]) of the study population. Chronic dissecting aneurysm was observed in 3 (7.5%) patients, whereas porcelain and shaggy aortas were noted in 6 (15.0%) and 2 (5.0%), respectively. There were 2 (5.0%) patients with a prior history of thoracic endovascular repair due to arch aneurysm and aortic dissection, and each patient was associated with stent-induced endoleak (type 3) and stent-induced new entry in the arch, respectively. Aortic valve surgery, such as aortic valve plasty (n = 2 [5.0%]), aortic valve replacement (n = 4 [10.0%]), and valve-

TABLE 1. Baseline characteristics of sternotomy and mini-access groups before and after inverse-probability of treatment weighting (IPTW)

	Before weighting				After IPTW			
Variable	Mini-access (n = 40)	Sternotomy (n = 55)	*P* value	SMD	Mini-access (n = 40)	Sternotomy (n = 55)	*P* value	SMD
Age (y)	69.5 (65.5-76.3)	71.0 (65.5-76.3)	1.00	0.201	67.9 (64.0-75.0)	70.0 (65.0-76.6)	.42	0.035
Male sex	32 (80.0)	39 (70.9)	.44	0.212	30.0 (75.0)	40.3 (73.3)	.87	0.040
BSA (m^2)	1.75 ± 0.19	1.74 ± 0.18	.88	0.031	1.73 ± 0.17	1.73 ± 0.18	.96	0.010
Hb (g/dL)	12.8 ± 1.5	12.9 ± 1.6	.77	0.061	13.0 ± 1.4	13.0 ± 1.5	.89	0.031
eGFR (mL/min/1.73 m^3)	71.7 (62.3-81.6)	72.7 (59.0-85.2)	.98	0.021	72.6 (61.7-78.8)	72.9 (60.3-85.2)	.97	0.042
Comorbid conditions								
HTN	27 (67.5)	46 (83.6)	.11	0.382	30.3 (75.8)	43.0 (78.2)	.81	0.058
DM	6 (15.0)	13 (23.6)	.43	0.220	7.3 (18.4)	12.2 (22.2)	.70	0.095
Chronic lung disease	4 (10.0)	8 (14.5)	.73	0.139	3.1 (7.8)	6.5 (11.9)	.51	0.136
History of PCI	11 (27.5)	5 (9.1)	.037	0.490	6.8 (17.0)	6.2 (11.4)	.46	0.163
LVEF	62.5 (58.8-65.0)	62.0 (59.0-65.0)	.96	0.085	62.9 (58.1-65.3)	62.0 (59.0-65.0)	.80	0.009
Afib	3 (7.5)	3 (5.5)	1.00	0.083	1.7 (4.4)	2.4 (4.3)	1.00	0.001
CVA	7 (17.5)	2 (3.6)	.058	0.463	3.9 (9.9)	2.7 (5.0)	.38	0.188
Dialysis	1 (2.5)	1 (1.5)	1.00	0.047	0.7 (1.8)	1.0 (1.7)	.99	0.003
PAOD	1 (2.5)	2 (3.6)	1.00	0.066	0.7 (1.8)	1.6 (2.9)	.71	0.070
Aortic disease	8 (20.0)	4 (7.3)	.13	0.377	4.6 (11.6)	6.3 (11.5)	.99	0.004
TEVAR	2 (5)	1 (1.5)						
Disease entity								
Degenerative aneurysm	29 (72.5)	34 (61.8)	.39	0.229	29.0 (72.5)	36.4 (66.2)	.58	0.136
Chronic dissection	3 (7.5)	9 (16.4)	.33	0.276	5.8 (14.6)	8.2 (15.0)	.97	0.011
Porcelain aorta	6 (15.0)	4 (7.3)	.38	0.248	4.0 (9.9)	5.1 (9.2)	.92	0.023
Shaggy aorta	2 (5.0)	8 (14.5)	.24	0.326	1.2 (3.0)	5.2 (9.5)	.13	0.273
Concomitant operation								
Bentall	0 (0.0)	2 (3.6)	.62	0.275	0.0 (0.0)	1.3 (2.4)	.24	0.222
VSRR	1 (2.5)	3 (5.5)	.85	0.152	0.6 (1.5)	1.9 (3.5)	.45	0.129
AVP	2 (5.0)	0 (0.0)	.34	0.324	3.3 (8.2)	0.0 (0.0)	.12	0.422
AVR	4 (10.0)	6 (10.9)	1.00	0.030	2.3 (5.7)	5.5 (10.0)	.38	0.162
Ablation	3 (7.5)	4 (7.3)	1.00	0.009	1.7 (4.4)	3.0 (5.5)	.77	0.051

Values are presented as median (interquartile range), n (%), or mean ± SD. *IPTW*, Inverse-probability of treatment weighting; *SMD*, standardized mean difference; *BSA*, body surface area; *Hb*, hemoglobin; *eGFR*, estimated glomerular filtration rate; *HTN*, hypertension; *DM*, diabetes mellitus; *PCI*, percutaneous coronary intervention; *LVEF*, left ventricular ejection fraction; *Afib*, atrial fibrillation; *CVA*, cerebrovascular accident; *PAOD*, peripheral arterial obstructive disease; *TEVAR*, thoracic endovascular repair; *VSRR*, valve sparing root replacement; *AVP*, aortic valve plasty; *AVR*, aortic valve replacement.

sparing root replacement (n = 1 [2.5%]), constituted the majority of concomitant procedures performed. Additionally, ablation of atrial fibrillation through a left atrial roof approach was performed in 3 (7.5%) patients, as a combined procedure.

Operative Profiles and Outcomes

Upper mini-sternotomy down to the third intercostal space accounted for the majority of the patients (n = 32 [80.0%]), whereas the larger incision down to the fourth intercostal space was preferred in the initial phase (based on personal experiences). In most patients (n = 27 [67.5%]) in this study the innominate artery was used as the primary site for arterial inflow cannulation. In 27.5% of the patients (n = 11), the ascending aorta was selected as the cannulation site. The utilization of the axillary and femoral arteries was limited to a few patients (Table 2). In accordance with the decision-making tree mentioned earlier in Figure 2, the arch-first approach utilizing a trifurcate graft was the most frequently employed, accounting for a total of 18 (45.0%) patients. A distal-first strategy utilizing a 4-branch graft was implemented in 12 (30.0%) patients, whereas in a selective manner, head vessel anastomosis using the island technique was performed in 10 (25%) patients. The representative preoperative and postoperative images of computed tomography scan were shown in Figure E1 and Video 2. The inverted grafting technique was utilized in 19 (47.5%) patients (Figure 1).

Mean nasopharyngeal temperature at the time of lower body ischemia was 26.3 ± 1.3 °C, and median durations of lower body ischemia, cardiac ischemic, and CPB were 23.4 minutes (IQR, 18.0-29.0 minutes), 66.7 minutes (IQR, 50.1-78.2 minutes), and 100.0 minutes (IQR, 87.1-107.4 minutes), respectively.

There was no early mortality. Disabling stroke occurred in 2 (5.0%) patients, in which brain magnetic resonance imaging findings were suggestive of multiple embolic infarctions. One additional patient (2.5%) experienced nondisabling motor deficit, which was completely resolved at the time of hospital discharge. With regard to other major clinical end points, there were de novo dialysis (n = 1 [2.5%]), surgical site bleeding re-explored (n = 1 [2.5%]), and femoral cannulation site injury, which required re-exploration (n = 1 [2.5%]).

Comparative Outcomes

During the study period, a total of 55 patients (age, 71.0 years; IQR, 65.5-76.3 years; 70.9% men) undergoing TAR using the full-sternotomy approach met the eligible criteria to serve as the control group. Baseline variables before and after the IPTW adjustment in the 2 groups are available in Table 1. The love-plots, indicating stabilization of SMD, are shown in Figure E2. Regarding the procedural profiles, the mini-access group demonstrated less frequent uses of the axillary cannulation (P = .004) and distal-first 4-branch anastomosis procedure (P = .019), but more frequent uses of the inverted grafting technique ($P < .001$) and island arch anastomosis (P = .035) (Table E1). Compared with the control group, the mini-access group

TABLE 2. Operative characteristics of patients in the mini-access total arch replacement group (N = 40)

Variable	Result
Third ICS upper sternotomy	32 (80.0)
Fourth ICS upper sternotomy	8 (20.0)
Bypass strategy	
Ascending aorta cannulation	11 (27.5)
Innominate artery cannulation	21 (52.5)
Femoral cannulation	1 (2.5)
Axillary + ascending	2 (5.0)
Innominate + femoral	6 (15.0)
Anastomosis strategy	
Arch first anastomosis	18 (45.0)
Distal first four branch anastomosis	12 (30.0)
Distal first island anastomosis	10 (25.0)
Elephant trunk insertion	13 (32.5)
Inverted graft technique	19 (47.5)

Values are presented as n (%). *ICS*, Intercostal space.

VIDEO 2. Representative serial preoperative and postoperative computed tomography (CT) scan images for each surgical strategy employed in mini-access total arch replacement. *ICS*, Intercostal space. Video available at: https://www.jtcvs.org/article/S2666-2507(23)00478-9/fulltext.

had significantly higher nasopharyngeal temperature achieved during low body ischemia (26.3 ± 1.3 °C vs 25.0 ± 1.0 °C; $P < .001$), and durations of cardiac ischemia, CPB, and the entire procedure were significantly shorter (all P values < .001), saving only the lower body ischemic time ($P = .41$) after the IPTW adjustment (Table 3).

Although there were no significant differences in the occurrence of primary end points (mortality and disabling stroke) between the groups under crude comparisons, the mini-access group showed a lower rate of developing the composite of secondary end points (major complications) than the sternotomy control group (10.0% vs 29.1%; $P = .046$). After the IPTW adjustment, the mini-access group showed significantly lower rates of primary composite end point (mortality + any stroke) (odds ratio, 0.88; 95% CI 0.78-1.00; $P = .049$) and major complications (odds ratio, 0.79; 95% CI, 0.68-0.92; $P = .003$) (Table 4 and Table E2). In the 3-year follow-up data, whereas the mini-access group demonstrated better trends compared with the sternotomy group, there were no statistically significant differences observed in survival rates (hazard ratio [HR], 1.05; 95% CI, 0.33-3.34; $P = .93$), incidences of stroke (HR, 0.31; 95% CI, 0.08-1.22; $P = .09$), or composite outcomes of death and stroke (HR, 0.64; 95% CI, 0.23-1.80; $P = .40$) between cases of mini-access and sternotomy TAR (Figure E3). The mini-access group significantly showed a shorter length of stay and numerical rating scale pain score than the sternotomy group (all P values < .001) (Figure 3).

DISCUSSION

In this study, we aimed to investigate the clinical effectiveness of TAR using a mini-access approach and compare its surgical risks with those of the traditional approach. In our study, the patients who underwent mini-access TAR exhibited comparable outcomes with the sternotomy group. Moreover, for the composite outcome, including major complications that may occur after the surgery, such as postoperative stroke, the mini-access TAR group demonstrated more favorable outcomes.

Recent meta-analyses have shown that minimally invasive surgery, at least for AVR, has superior outcomes, including lower complication rates and better 5-year survival rates.[16] Therefore, several experienced centers now consider the minimal invasive approach as their primary choice. However, application of minimally invasive approach in surgeries related to the aorta is very limited due to technical complexity and challenging learning curves. In TAR cases, it is essential to consider not only the replacement of the entire aortic arch and its supra-aortic branching arteries, which cause stroke/neurological complications due to its atherosclerotic nature but also the protection of the myocardium, as well as cerebral and visceral protection. Therefore a meta-analysis has been conducted for the ascending aorta and root surgery, with no significant clinical outcomes.[17] In the context of arch surgery, most literature are reports of individual centers level,[18-20] with a focus on hemiarch/proximal aortic arch replacement procedures. Our study focused on patients undergoing TAR with extensive aortic pathology involving the proximal descending aorta, including those with distal anastomosis performed on the proximal descending aorta. Moreover, we've implemented the mini-access TAR strategy without employing exclusion criteria except some cases as mentioned in the Methods section. When dealing with an aneurysm of a larger size in the aortic arch, the mini-access surgical field tends to be more favorable because space-occupying aneurysmal lesions provide ample room for efficient TAR procedures. For these reasons, we've also consistently applied the same criteria to patients with genetic aortic diseases such as Marfan syndrome or Loeys-Dietz syndrome. Additionally, the comparative aspect of our study evaluated the mini-access approach versus the conventional surgical approach, which enhances the significance of the study findings.

The mini-access group demonstrated a notable reduction in the surgery time compared with the sternotomy group, which was achieved using a tailored and systematic surgical approach detailed in Figure 2. First, the mini-access group actively used the inverted graft technique ($P < .001$) for

TABLE 3. Bypass and operative profile of the sternotomy and mini-access groups before and adjustment using inverse-probability of treatment weighting (IPTW)

Variable	Before weighting: Mini-access (n = 40)	Before weighting: Sternotomy (n = 55)	Before weighting: P value	After IPTW: Mini-access (n = 40)	After IPTW: Sternotomy (n = 55)	After IPTW: P value
Lowest nasopharyngeal temperature (°C)	26.4 ± 1.2	24.9 ± 1.1	<.001	26.3 ± 1.3	25.0 ± 1.0	<.001
Lower body ischemic time (min)	22.5 (17.8-28.3)	23.0 (18.5-34.0)	.30	23.4 (18.0-29.0)	23.6 (19.5-35.0)	.41
ACC time (min)	61.5 (47.0-77.3)	101.0 (79.0-131.0)	<.001	66.7 (50.1-78.2)	97.0 (77.9-119.2)	<.001
CPB time (min)	101.0 (89.8-112.3)	186.0 (165.5-216.0)	<.001	100.0 (87.1-107.4)	186.4 (165.4-210.9)	<.001
Entire procedure time (min)	273.5 (246.8-294.3)	427.00 (374.5-505.0)	<.001	268.0 (235.4-285.0)	419.2 (368.9-501.4)	<.001

Values are presented as mean ± SD or median (interquartile range). *IPTW*, Inverse-probability of treatment weighting; *ACC*, aortic crossclamp; *CPB*, cardiopulmonary bypass time.

TABLE 4. Comparison of perioperative clinical outcomes between the sternotomy and mini-access groups using multivariable logistic regression analysis

Variable	Mini-access (n = 40)	Sternotomy (n = 55)	*P* value	IPTW-adjusted OR	95% CI	*P* value
Primary end points						
In-hospital mortality	0 (0.0)	3 (5.6)	.36	0.98	0.94-1.04	.53
Disabling stroke	2 (5.0)	7 (12.7)	.36	0.95	0.85-1.06	.34
Composite of death and stroke	3 (7.5)	9 (16.4)	.33	0.88	0.78-1.00	.049
Secondary end points						
Major complications	4 (10.0)	16 (29.1)	.046	0.79	0.68-0.92	.003
Stroke	3 (7.5)	9 (16.4)				
De novo dialysis	1 (2.5)	5 (9.1)				
LCOS	0 (0.0)	4 (7.3)				
Postoperative bleeding	1 (2.5)	3 (5.5)				
Peripheral vessel complication	1 (2.5)	2 (3.6)				
Lung complication need ECMO	0 (0.0)	2 (3.6)				
GI complication	0 (0.0)	3 (5.5)				
Graft infection	0 (0.0)	3 (5.5)				

Values are presented as n (%) unless otherwise noted. Using multivariable logistic regression analysis (detailed analysis data are presented in Table E2). *IPTW*, Inverse-probability of treatment weighting; *OR*, odds ratio; *CI*, confidence interval; *LCOS*, low cardiac output syndrome; *ECMO*, extracorporeal membrane oxygenation.

anastomosis strategy, resulting in a relatively low use of 4-branch graft (*P* = .019). As previously reported by our institution,[15] the inverted graft technique is an efficient method for performing arch distal anastomosis in a limited field of view, with excellent hemostatic effects. This efficiency can be maximized when used together with a trifurcated graft to proceed with surgery using the arch-first strategy. In this study, this strategy was applied to 19 patients, accounting for 47.5% of the total study population. Second, the island anastomosis was actively used in selectively eligible patients (*P* = .035). As a result, aortic crossclamp and CPB time, including the entire procedural time, were statistically

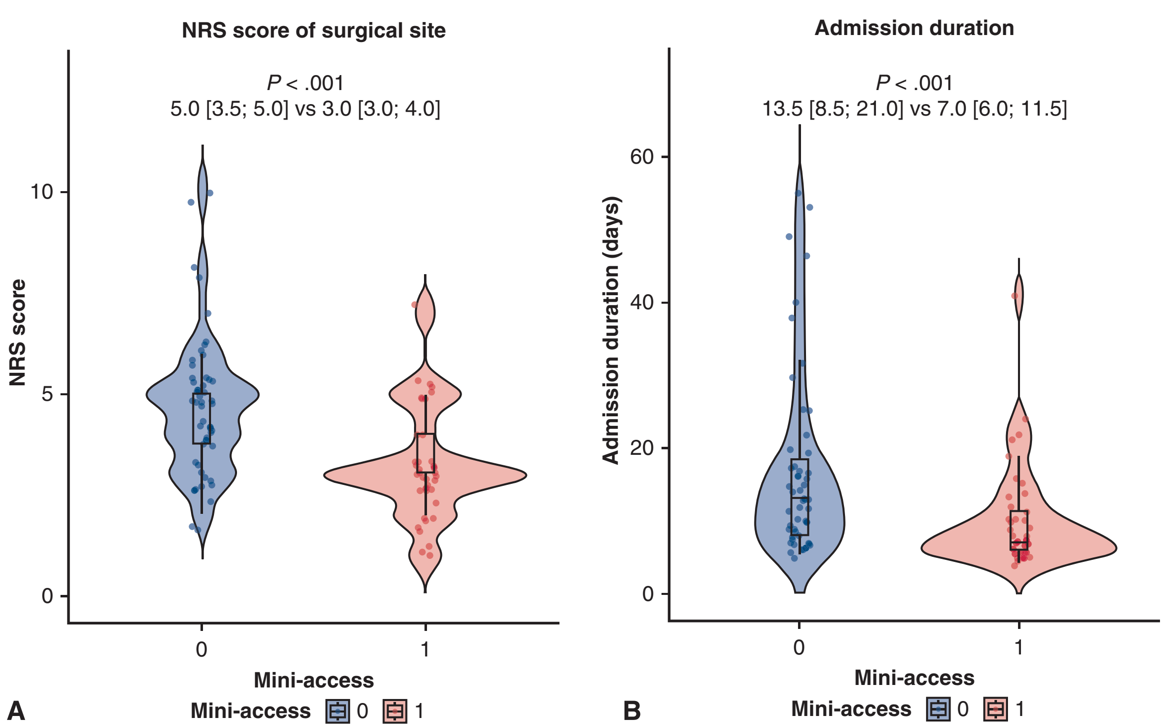


FIGURE 3. Violin plots comparing outcomes based on each approach, sternotomy (*blue*), and mini-access (*red*) total arch replacement. The *box plots within the violin plots* indicate the median and interquartile ranges. A, Surgical site pain measured using the numerical rating scale (*NRS*) among the patients, excluding in-hospital death. B, Admission duration among the patients, excluding in-hospital death. The *P* values were calculated using the Kruskal-Wallis test.

significantly lower (P < .001) in mini-access group compared with the sternotomy group, and body temperature could be maintained at a higher level (P < .001). The largest propensity score-matched analysis focusing on proximal aortic surgery also revealed that the minimally invasive approach group had a decreased operative time, emphasizing the significance of an efficient technique.[21]

According to a recent study that presented a predictive model for risk factors associated with stroke occurrence during TAR in patients with type A aortic dissection, the duration of CPB time serves as a statistically significant factor in the incidence of stroke.[22] Moreover, a study provided direct evidence of microemboli in the brain of patients who underwent open-heart surgery with CPB, showing that longer CPB duration was associated with an increased risk of microemboli.[23] In our study, there was a significant reduction in the incidence of postoperative stroke in the mini-access TAR group compared with the sternotomy group. This favorable outcome could be attributed to the potential effect of minimizing CPB time through the systematical adoption of decision-making algorithm for TAR. In other words, the improved clinical outcomes observed in the hard end points may not solely be attributed to the mini-access approach itself, but rather to the implementation of customized and stratified surgical strategies that could have influenced favorable results (Figure 4).

In addition to pursuing efficient surgical strategies to reduce CPB time, we tried to minimize the use of retrograde perfusion via the femoral artery and preferred innominate artery cannulation for arterial inflow. This strategy aimed to minimize potential retrograde embolization by using the innominate artery cannulation and maintaining continuous cerebral perfusion during the debranching process with a closed system. Studies have indicated that utilizing a closed system for bypass operation can maintain perfusion pressure and potentially offer brain protection during the procedure, which supports the strategies adopted in the present study.[24]

Apart from the stroke and mortality, the mini-access group demonstrated a statistically significant reduction in the incidence of composite major complications, including renal failure, postoperative bleeding, lung complications necessitating reintubation, such as extracorporeal membrane oxygenation support, and infections. These findings are similar to the results of previous meta-analytical studies on minimal invasive aortic valve replacement, further supporting the consistent efficacy of the mini-access approach.[16] In addition to the lower risks of major complications observed, the mini-access approach demonstrated not only cosmetic advantages but also a lower level of postoperative pain and shorter hospital stay (Figure 3). These findings highlight the potential benefits of the mini-access

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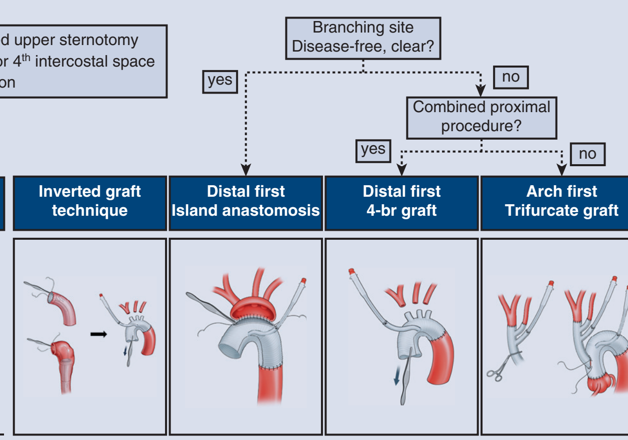
Outcomes of Mini-Access Open Total Arch Replacement

Dec 2018 - Jun 2022

Patients undergone Total Arch Replacement
- Mini-upper sternotomy : 40 patients
- Sternotomy : 55 patients

- Partial J/L-shaped upper sternotomy
- Through the 3rd or 4th intercostal space
- 5-8cm skin incision



Comparison of perioperative clinical outcomes between the sternotomy group and mini-access group

Variable	Mini-access (n = 40)	Sternotomy (n = 55)	P value	IPTW adjusted OR	95% CI	P value
Primary endpoints, n (%)						
In-hospital mortality	0 (0.0%)	3 (5.6%)	.36	0.98	0.94 - 1.04	.53
Disabling stroke	2 (5.0%)	7 (12.7%)	.36	0.95	0.85 - 1.06	.34
Composite of death and stroke	3 (7.5%)	9 (16.4%)	.33	0.88	0.78 - 1.00	.049
Secondary endpoints, n (%)						
*Major complications	4 (10.0%)	16 (29.1%)	.046	0.79	0.68 - 0.92	.003

Using mutivariable logistic regression analysis
***Major complications**: Stroke, De nova dialysis, Low cardiac output syndrome, postoperative bleeding, peripheral vessel complication, Lung complication need extracorporeal membrane oxygenation, Gastrointestinal complication, Graft infection
CI = Confidence Interval, IPTW = Inverse-Probability of Treatment Weighting, OR = Odds Ratio.

The outcomes of our study suggest that **Total Arch Replacement** can be performed through **upper mini-sternotomy** with reasonable safety and efficiency. If **optimal surgical strategies tailored to each patient** are devised to ensure efficient execution within a limited space, this technique could serve as a viable **alternative option in aortic arch surgery**.

FIGURE 4. Graphical abstract. *IPTW*, Inverse-probability of treatment weighting; *OR*, odds ratio; *CI*, confidence interval; *br*, branch.

approach, including improved patient satisfaction, enhanced recovery, and reduced health care costs.

Limitations

This study has several limitations. First, its retrospective nature, single-center design, and observational approach inherently introduced biases that cannot be fully attenuated, even with meticulous application of IPTW to account for potential confounding variables. Second, it should be noted that the operations included in this study were conducted exclusively at a high-volume aortic center where aortic arch replacement is routinely performed. Furthermore, this study specifically focuses on mini-access TAR performed by a single surgeon. Consequently, caution should be exercised when generalizing these findings to centers with lower volumes. Comparing outcomes between a single surgeon's mini-access TAR and multisurgeon sternotomy TAR could potentially introduce selection bias. However, our objective in presenting comparative data is to demonstrate the feasibility and safety of the mini-access TAR by tailored surgical strategies, rather than emphasizing the superiority of the mini-access approach. In follow-up research, as multiple surgeons adopt the mini-access approach for TAR, we plan to compile data for a study comparing outcomes between sternotomy and the mini-access approach. Finally, the sample size was relatively small, which requires further validation of the results from larger data in broader experiences.

CONCLUSIONS

The results of our study suggest that TAR can be performed using upper ministernotomy with reasonable safety and efficiency. Moreover, through the implementation of strategies aimed at promoting efficient surgical interventions within confined spaces, a notable reduction in CPB time was attained, which can also be utilized for the standard full-sternotomy approach. If optimal surgical strategies tailored to each patient are devised to ensure efficient execution within a limited space, this technique would serve as a viable alternative option in aortic arch surgery.

Conflicts of Interest Statement

The authors reported no conflicts of interest.

The *Journal* policy requires editors and reviewers to disclose conflicts of interest and to decline handling manuscripts for which they may have a conflict of interest. The editors and reviewers of this article have no conflicts of interest.

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Key Words: minimal invasive surgery, total arch replacement, aorta

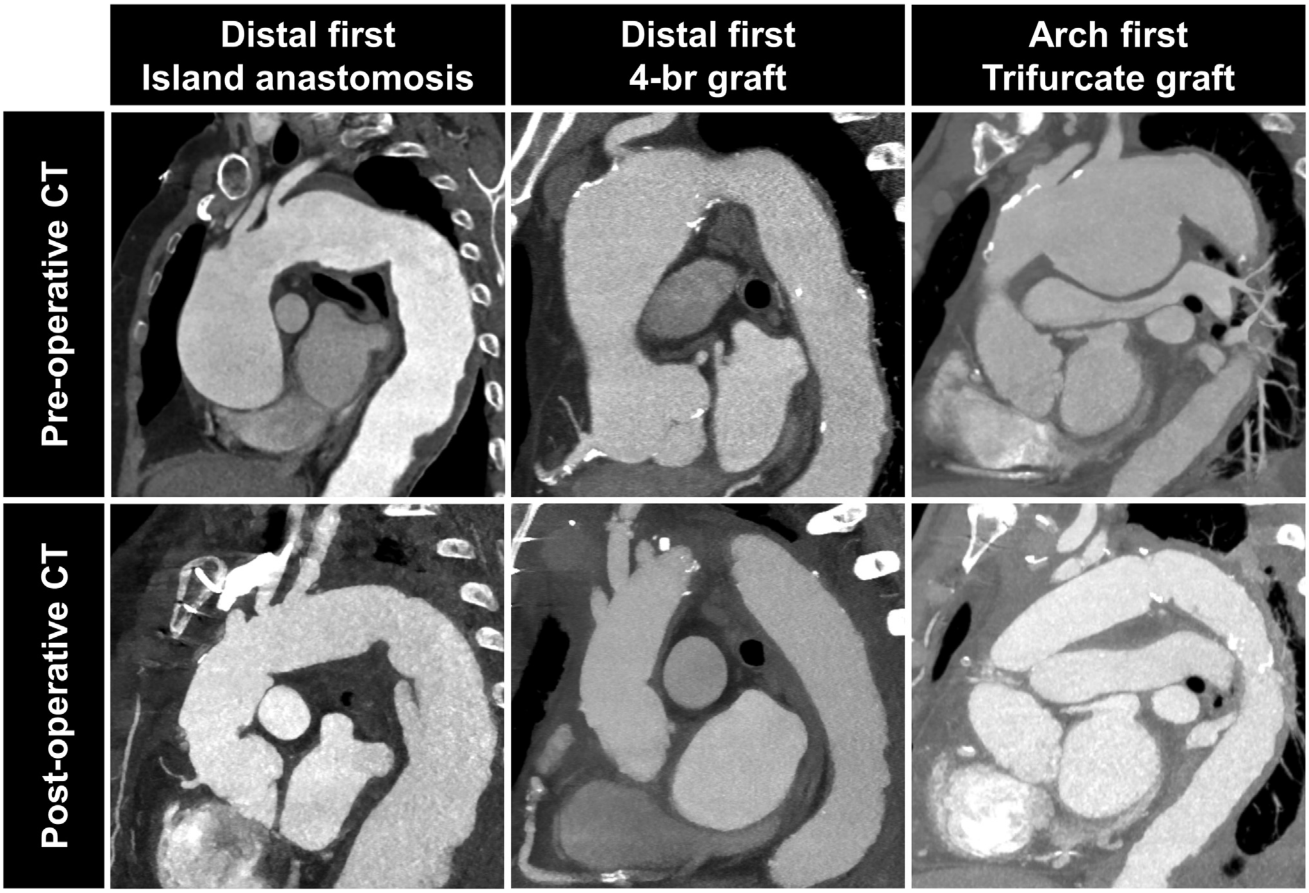

FIGURE E1. Representative preoperative and postoperative computed tomography (*CT*) scan images for each surgical strategy employed in mini-access total arch replacement. *br*, Branch.

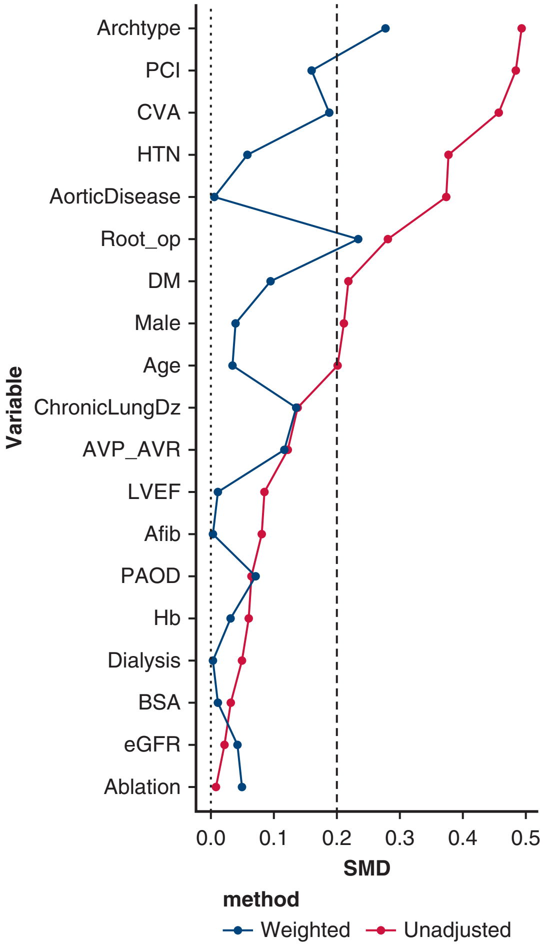

FIGURE E2. Standardized mean difference (*SMD*) before (*red*) and after (*blue*) inverse probability of treatment weighting (IPTW). *PCI*, Percutaneous coronary intervention; *CVA*, cerebrovascular accident; *HTN*, hypertension; *DM*, diabetes mellitus; *Dz*, disease; *AVP*, aortic valve plasty; *AVR*, aortic valve replacement; *LVEF*, left ventricular ejection fraction; *Afib*, atrial fibrillation; *PAOD*, peripheral arterial obstructive disease; *Hb*, hemoglobin; *BSA*, body surface area; *eGFR*, estimated glomerular filtration.

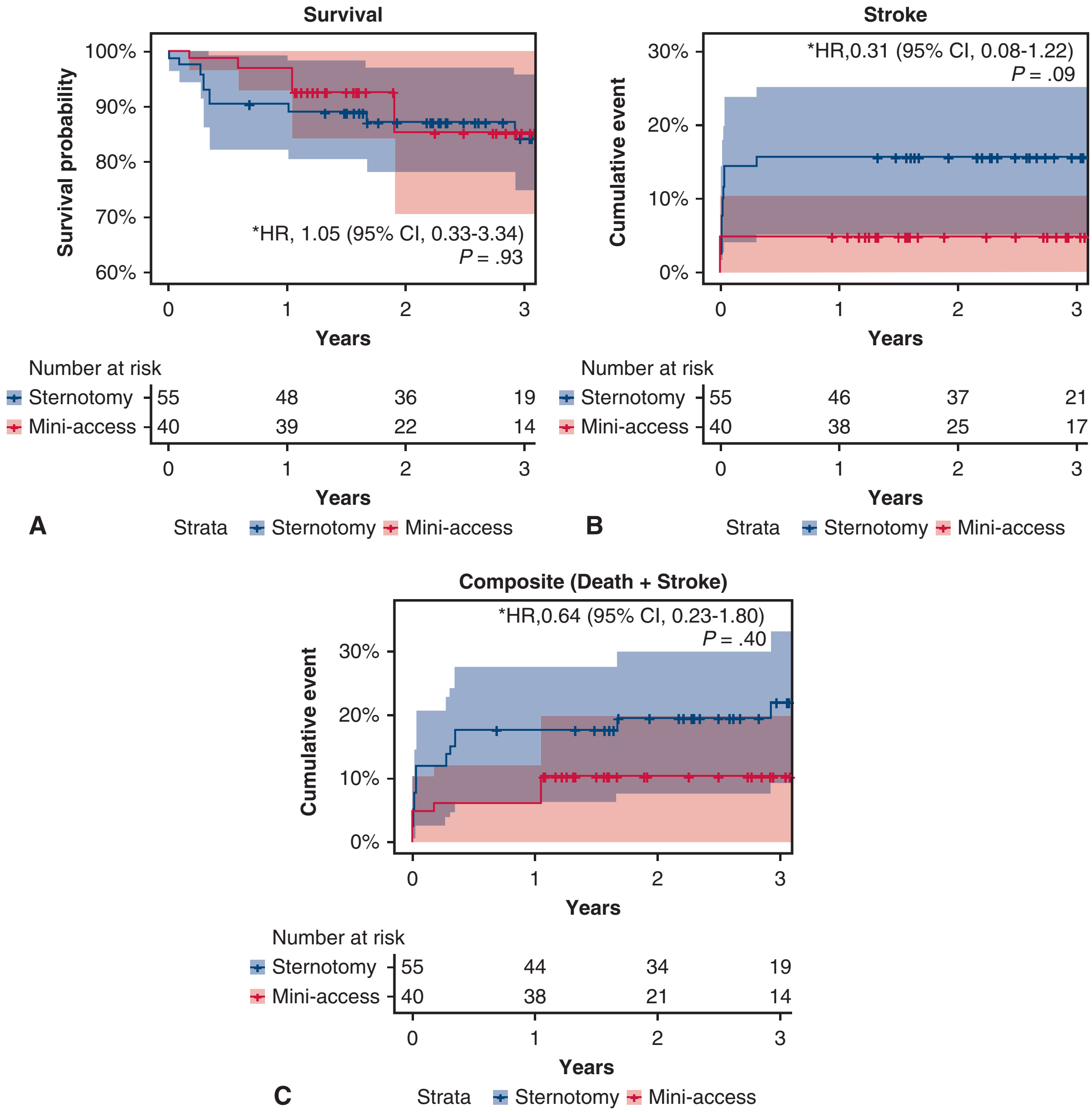

FIGURE E3. Midterm (3-year) follow-up data comparison between mini-access and sternotomy total arch replacement following adjustment using inverse probability of treatment weighting (IPTW). A, Survival. B, Stroke. C, Composite outcomes (death and stoke). *HR*, Hazard ratio; *CI*, confidence interval.

TABLE E1. Operative characteristics of the sternotomy and mini-access groups

Variable	Mini-access (n = 40)	Sternotomy (n = 55)	*P* value	SMD
Third ICS upper sternotomy	32 (80.0)			
Fourth ICS upper sternotomy	8 (20.0)			
Bypass strategy				
Ascending aorta cannulation	11 (27.5)	12 (21.8)	.69	0.132
Innominate artery cannulation	21 (52.5)	19 (34.5)	.12	0.368
Femoral cannulation	1 (2.5)	5 (9.1)	.38	0.285
Axillary + ascending	2 (5.0)	17 (30.9)	.004	0.717
Innominate + femoral	6 (15.0)	4 (7.3)	.38	0.248
Anastomosis strategy				
Arch first anastomosis	18 (45.0)	22 (40.0)	.78	0.101
Distal first 4 branch anastomosis	12 (30.0)	31 (56.4)	.019	0.552
Distal first island anastomosis	10 (25.0)	4 (7.3)	.035	0.497
Elephant trunk insertion	13 (32.5)	26 (47.3)	.26	0.285
Inverted graft technique	19 (47.5)	3 (5.5)	<.001	1.080

Values are presented as n (%). *SMD*, Standardized mean difference; *ICS*, intercostal space.

TABLE E2. Multivariable logistic regression analysis for the outcomes of patients undergoing total arch replacement surgery

	Stroke				Disabling stroke			
	Univariable		Multivariable		Univariable		Multivariable	
Variable	OR (95% CI)	*P* value	OR (95% CI)	*P* value	OR (95% CI)	*P* value	OR (95% CI)	*P* value
Age	1.01 (1.00-1.02)	.095	1.01 (1.00-1.01)	.039*				
Diabetes mellitus					1.13 (0.97-1.33)	.13	1.15 (1.01-1.31)	.036*
PCI history	1.21 (0.96-1.53)	.12	1.28 (1.07-1.52)	.007†				
Disease entity								
Degenerative aneurysm	Reference				Reference			
Chronic dissecting aneurysm	0.92 (0.75-1.12)	.41			0.95 (0.79-1.12)	.52	0.94 (0.81-1.09)	.38
Porcelain aorta	0.92 (0.72-1.17)	.49			0.97 (0.78-1.19)	.76	0.98 (0.82-1.18)	.85
Shaggy aorta	1.25 (0.95-1.66)	.12			1.32 (1.03-1.69)	.031*	1.27 (1.03-1.56)	.031*
Mini-access	0.90 (0.79-1.03)	.13	0.88 (0.78-1.00)	.049*				
	In-hospital mortality				Major complications			
Male	1.08 (0.99-1.18)	.08	1.05 (0.99-1.11)	.11				
BSA					0.79 (0.40-1.58)	.51	0.73 (0.47-1.14)	.17
Hypertension					1.13 (0.92-1.39)	.26	1.16 (0.97-1.39)	.10
Dialysis history	0.83 (0.65-1.07)	.15	0.85 (0.70-1.04)	.12	1.80 (0.86-3.79)	.13	1.50 (0.85-2.65)	.169
Chronic lung disease					1.41 (1.05-1.90)	.028*	1.39 (1.08-1.78)	.012*
PCI history					1.31 (0.98-1.76)	.074	1.29 (1.03-1.61)	.030*
Disease entity								
Degenerative aneurysm	Reference		Reference					
Chronic dissecting aneurysm	0.99 (0.92-1.08)	.86	1.00 (0.93-1.08)	.99				
Porcelain aorta	1.00 (0.91-1.11)	.94	1.01 (0.92-1.10)	.89				
Shaggy aorta	1.42 (1.26-1.59)	<.001‡	1.40 (1.27-1.56)	<.001‡				
Mini-access					0.78 (0.66-0.91)	.003†	0.79 (0.68-0.92)	.003†

OR, Odds ratio; *CI*, confidence interval; *PCI*, percutaneous coronary intervention; *BSA*, body surface area. *$P < .05$. †$P < .01$. ‡$P < .001$.