In elective arch surgery with circulatory arrest, does the arterial cannulation site really matter? A propensity score analysis of right axillary and innominate artery cannulation

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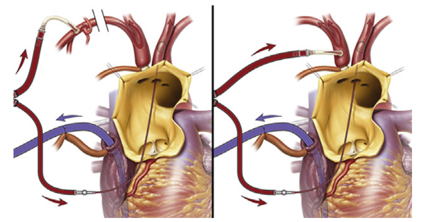
ABSTRACT

Objective: The preferred arterial cannulation site for elective proximal aortic procedures requiring circulatory arrest varies, and different sites have been tried. We evaluated the relationships between arterial cannulation site and adverse outcomes, including stroke, in patients undergoing elective aortic arch surgery.

Methods: We reviewed the records of 938 patients who underwent elective hemiarch or total arch surgery with circulatory arrest between 2006 and 2016. Five cannulation sites were used: the right axillary (n = 515; 54.9%), innominate (n = 376; 40.1%), and right common carotid arteries (n = 15; 1.6%), each with a side graft; the ascending aorta (n = 19; 2.0%); and the femoral artery (n = 13; 1.4%). Multivariable logistic regression analysis was used to model the effects of cannulation site on adverse outcomes for the entire cohort and for a subcohort of 891 patients who underwent innominate or axillary artery cannulation. Propensity-matching yielded 564 patients (282 pairs) from the right axillary and innominate artery groups.

Results: For the entire cohort, mortality, stroke, and composite adverse outcome (operative death or persistent stroke or renal failure at hospital discharge) rates were 7.0%, 4.1%, and 9.8%. In the multivariable analysis of the axillary/innominate subcohort, cannulation site did not independently predict operative mortality, persistent stroke, or composite adverse event. These results were confirmed with the propensity-matched analysis, where both axillary and innominate artery cannulation provided equivalent composite adverse event rates, operative death rates, and overall stroke rates.

Conclusions: During elective arch surgery, right axillary artery cannulation and innominate artery cannulation (both via a side graft) produce excellent results and can be used interchangeably. (J Thorac Cardiovasc Surg 2018;155:1953-60)



Axillary (*left*) and innominate (*right*) inflow cannulation for cardiopulmonary bypass.

Central Message

Axillary artery cannulation and innominate artery cannulation (both via a side graft) provide excellent results and can be used interchangeably.

Perspective

In the modern era, with modern imaging modalities, the cannulation site should be chosen in a way that facilitates the operation and minimizes complications. Different cannulation strategies can be used to establish arterial inflow for elective proximal and total arch cases. Innominate and axillary artery cannulation with a side graft provide equivalent results, with no clear winner.

See Editorial Commentary page 1961.

Various cannulation techniques have been used for proximal thoracic aortic surgery, although which cannulation site is best remains controversial among cardiothoracic surgeons.[1-4] Neuroprotection strategies target minimizing circulatory arrest time and reducing cerebral metabolic demand with various levels of hypothermia. The equivocal evidence supporting the use of different cannulation strategies during elective proximal and total arch surgery suggests that "there is more than one way to skin a cat." Various strategies, including direct or indirect (ie, via a side graft) cannulation of the right axillary,

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Abbreviations and Acronyms

ACP = antegrade cerebral perfusion
CI = confidence interval
CPB = cardiopulmonary bypass
DHCA = deep hypothermic circulatory arrest
OR = odds ratio
SE = standard error

innominate, or right common carotid artery, can be used to provide antegrade cerebral perfusion (ACP) during circulatory arrest, thereby making straight deep hypothermic circulatory arrest (DHCA) unnecessary. Direct aortic cannulation under echocardiographic guidance is becoming increasingly popular. Femoral artery cannulation with DHCA, once the traditional approach for chronic conditions involving the aortic arch, is used by some today for acute conditions.[5] In this study, we evaluated different cannulation strategies with regard to their association with adverse outcomes in patients who underwent elective proximal or total arch surgery.

PATIENTS AND METHODS

Between 2006 and 2016, 5 different cannulation sites were used in 938 patients to establish cardiopulmonary bypass (CPB) during elective proximal arch surgery. Three arteries were cannulated with a side graft: axillary (n = 515), innominate (n = 376), and right common carotid (n = 15). The other 2 were cannulated directly: the aorta (n = 19) and the femoral artery (n = 13). The use of any additional cannulation site (eg, the side arm of the ascending aortic graft after replacement of the ascending aorta) during the rewarming period was not counted.

Hospital records, operative reports, and operative diagrams were retrieved from a prospectively maintained database. Informed consent was obtained for data collection whenever possible; Baylor College of Medicine's institutional review board, which approved the study, waived the consent requirement for patients who could not provide consent because of illness and whose family members were not available. Follow-up data were actively obtained through clinic visits, telephone calls to the patient or the patient's family, and communication with the patient's primary care doctor or cardiologist.

Patient characteristics were examined for a subcohort comprising the axillary and innominate cannulation groups (891 patients) and for the patients included in a propensity score analysis for axillary and innominate cannulation (564 patients, 282 pairs) (Table 1). In addition, patient characteristics were examined for the entire cohort of 938 patients (Table E1). Composite adverse event was defined as operative mortality, persistent (ie, at hospital discharge or at time of operative death) neurologic event (stroke or spinal cord injury), or persistent renal failure (need for hemodialysis). Outcome variables and intraoperative times have been previously defined.[3]

Operative Techniques

All 938 proximal aortic procedures were elective; these consisted of 696 proximal arch replacements (74.2%) and 242 total arch replacements (25.8%) with ACP (Table E1). No procedure involved retrograde cerebral perfusion or DHCA. In the early part of the study period, bilateral ACP was more commonly used for the complex cases that were expected to require a prolonged (>30 minutes) total ACP time. Over the years, our practice has changed. Recently, our default strategy has been to use bilateral ACP regardless of the total ACP time or the complexity of the procedure. The targeted nasopharyngeal temperature was approximately 20°C to 25°C during the period of low flow (10-15 mL/kg/min). Transesophageal echocardiography and near-infrared spectroscopy were used by the

TABLE 1. Preoperative characteristics of the axillary/innominate subcohort, overall and propensity-matched

	Overall				Propensity-matched cohort		
Characteristics	Overall (n = 891)	Axillary (n = 515)	Innominate (n = 376)	*P* value	Axillary (n = 282)	Innominate (n = 282)	Std mean diff
Age, y	60.5 ± 13.8	61.3 ± 13.6	59.5 ± 14.1	.036	61.1 ± 13.5	61.2 ± 13.6	0.6
Male	611 (68.6)	352 (68.3)	259 (68.9)	.923	195 (69.1)	187 (66.3)	6.1
Confirmed or suspected genetic disease	94 (10.5)	49 (9.5)	45 (12.0)	.286	17 (6.0)	17 (6.0)	0.0
Aortic aneurysm without dissection	707 (79.3)	368 (71.5)	339 (90.2)	<.001	240 (85.1)	241 (85.5)	0.9
Aortic dissection	184 (20.7)	147 (28.5)	37 (9.8)	<.001	42 (14.9)	41 (14.5)	0.9
Hypertension	765 (85.9)	439 (85.2)	326 (86.7)	.603	242 (85.8)	240 (85.1)	2.0
Diabetes	77 (8.6)	40 (7.8)	37 (9.8)	.333	21 (7.4)	22 (7.8)	1.3
Tobacco use, current or past	505 (56.7)	304 (59.0)	201 (53.5)	.112	159 (56.4)	160 (56.7)	0.7
NYHA class III or IV	215 (24.1)	155 (30.1)	60 (16.0)	<.001	49 (17.4)	58 (20.6)	7.7
Cardiac history*	214 (24.0)	119 (23.1)	95 (25.3)	.506	64 (22.7)	64 (22.7)	0.0
Pulmonary history†	214 (24.0)	119 (23.1)	95 (25.3)	.506	53 (18.8)	61 (21.6)	7.0
Renal history‡	214 (24.0)	119 (23.1)	95 (25.3)	.506	4 (1.4)	5 (1.8)	2.8
Cerebrovascular history§	111 (12.5)	75 (14.6)	36 (9.6)	.034	32 (11.3)	33 (11.7)	1.1
Previous proximal aortic repair‖	176 (19.8)	145 (28.2)	31 (8.2)	<.001	38 (13.5)	30 (10.6)	7.6
Redo sternotomy	268 (30.1)	214 (41.6)	54 (14.4)	<.001	63 (22.3)	53 (18.8)	8.3

Data are presented as mean ± standard deviation for continuous variables and n (%) for categorical variables. *NYHA*, New York Heart Association. *History of angina, myocardial infarction, coronary artery bypass grafting, percutaneous transluminal coronary angiography/stenting, or arrhythmia/heart block. †History of asthma or chronic obstructive pulmonary disease. ‡Initial serum creatinine level ≥3.0 mg/dL, renal failure necessitating hemodialysis, or renal insufficiency. §History of transient ischemic attack, stroke, carotid endarterectomy, or cerebral aneurysm. ‖Previous ascending aortic repair or aortic root replacement.

VIDEO 1. Axillary and innominate cannulation strategies. Video available at: http://www.jtcvsonline.org/article/S0022-5223(17)32893-3/fulltext.

anesthesia team. For blood pressure monitoring, we preferred to use the right radial arterial line, but quite often, the anesthesia team placed right and left radial arterial lines so that they could monitor the patient's blood pressure during cannulation. In redo cases, an additional femoral arterial line was used to monitor the blood pressure.

The timeline for our cannulation strategy was as follows: Early in the 10-year study period, for CPB, we cannulated the axillary artery with a side graft; however, in the last 6 to 7 years, we started using the innominate artery with a side graft, which became our preferred site on the basis of the results of our early experience (Video 1).[6] We have previously described our rationale for preferring innominate over axillary cannulation.[3,6] The common carotid artery was cannulated in patients whose innominate artery was short or aneurysmal. All 3 of these arteries were cannulated with an 8-mm side graft (10-mm for obese patients). Femoral artery cannulation was our default strategy for elective redo proximal aortic procedures when severe venous or aortic bleeding was encountered on sternal entry. In this series, the femoral artery was always cannulated directly, not through a side graft. Direct aortic cannulation was used in elective cases when malperfusion or inadequate flow was detected immediately after CPB was established. Our decision-making process is shown in Figure 1. Our proximal arch and total arch techniques have been previously described.[3,7] In all cases, a preoperative computed tomography scan was performed. Epiaortic ultrasound of the proximal thoracic aorta was not routinely used, but it was occasionally used in cases of malperfusion.

Statistical Analysis

Both a multivariable analysis and a propensity score-matching analysis were performed. For the propensity score-matching analysis, we estimated the propensity score by using a multivariate logistic regression model. We included the following preoperative covariates in the model: patient age, sex, confirmed or suspected genetic disease, hypertension, diabetes, tobacco use (current or past), New York Heart Association class III or IV, cardiac history, pulmonary history, renal history, cerebrovascular

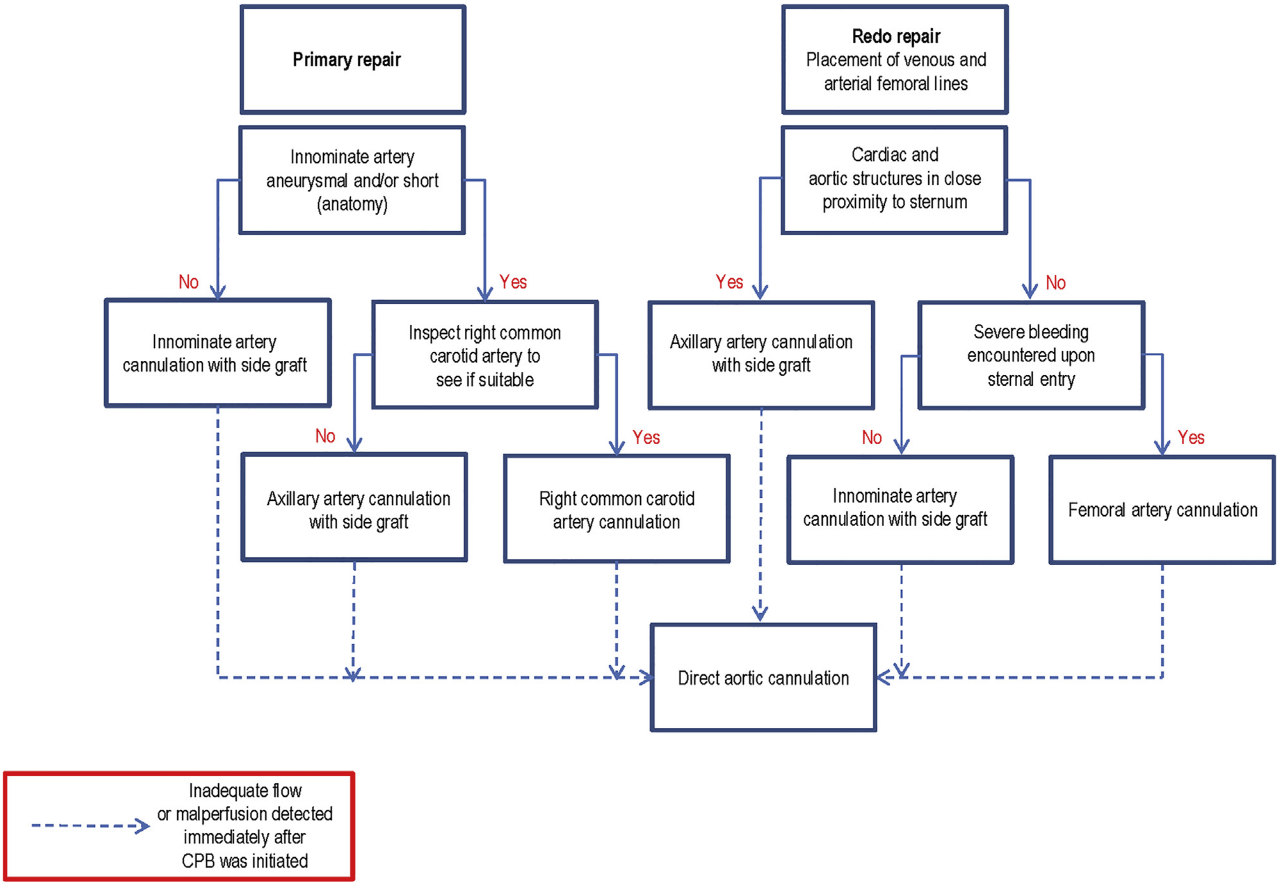

FIGURE 1. Diagram showing the decision-making process for arterial cannulation in elective aortic arch repair. *CPB*, Cardiopulmonary bypass.

TABLE 2. Short-term complications of the axillary/innominate subcohort, overall and propensity-matched

	Overall				Propensity-matched cohort		
Characteristics	Overall (n = 891)	Axillary (n = 515)	Innominate (n = 376)	*P* value	Axillary (n = 282)	Innominate (n = 282)	*P* value
Operative death*	58 (6.5)	37 (7.2)	21 (5.6)	.413	12 (4.3)	21 (7.4)	.150
Stroke, persistent	25 (2.8)	18 (3.5)	7 (1.9)	.21	8 (2.8)	6 (2.1)	.791
Overall stroke†	34 (3.8)	25 (4.9)	9 (2.4)	.086	13 (4.6)	8 (2.8)	.383
Composite adverse event‡	81 (9.1)	55 (10.7)	26 (6.9)	.07	21 (7.4)	25 (8.9)	.627
Renal dysfunction/insufficiency	65 (7.3)	43 (8.3)	22 (5.9)	.198	16 (5.7)	22 (7.8)	.405
Renal failure necessitating hemodialysis							
Transient	14 (1.6)	9 (1.7)	5 (1.3)	.824	1 (0.4)	5 (1.8)	.219
Permanent	31 (3.5)	21 (4.1)	10 (2.7)	.339	9 (3.2)	10 (3.5)	.99
Respiratory failure	200 (22.4)	143 (27.8)	57 (15.2)	<.001	71 (25.2)	52 (18.4)	.067
Tracheostomy	72 (8.1)	53 (10.3)	19 (5.1)	.007	24 (8.5)	19 (6.7)	.780
Heart block requiring pacemaker	61 (6.8)	38 (7.4)	23 (6.1)	.547	17 (6.0)	16 (5.7)	.99
Bleeding requiring operation	27 (3.0)	20 (3.9)	7 (1.9)	.123	8 (2.8)	6 (2.1)	.791

Data are presented as n (%). *Intraoperative, 30-day, or in-hospital death. †Persistent or transient stroke. ‡Operative death, persistent stroke, persistent renal failure necessitating hemodialysis, or persistent paraparesis/paraplegia.

history, previous proximal aortic repair, redo sternotomy, and aortic pathology.

A 1-to-1 matching without replacement by propensity score was performed by using the nearest neighbor method with a caliper of 0.05 standard deviation of the logit. Matching was carried out with the psmatch2 package in STATA (version 14; STATA, College Station, Tex; Computing Resource Center, Santa Monica, Calif). Balance in the baseline covariates of matched data was examined by using standardized differences. We compared the postoperative variables of the axillary artery group and innominate artery group by using the McNemar test. The standardized mean differences were reported. The overall survival rates of both groups were compared with the stratified log-rank test. The association between cannulation site and overall survival was evaluated with a Cox proportional hazards regression model stratified by matched pairs. The assumption of proportional hazards was examined with scaled Schoenfeld residuals.

For the multivariable analysis, we built a multivariable logistic regression model with the following postoperative variables: operative death, persistent stroke, overall stroke, renal dysfunction, bleeding requiring reoperation, respiratory failure, and composite adverse event. We first compared the outcomes of the innominate and the axillary groups by using univariate analyses and then entered the clinically relevant and statistically significant preoperative and intraoperative variables into the model and applied a backward selection method to choose the final multivariable models with the smallest Akaike information criterion.

For the models of our entire cohort (n = 938) and our axillary/innominate subcohort (n = 891), the following variables were considered for model entry: cannulation site, aortic pathology, age, tobacco use (current or past), New York Heart Association class III or IV, cardiac history, pulmonary history, renal history, cerebrovascular history, redo sternotomy, CPB time, full arch procedure, concomitant aortic root repair or replacement, concomitant coronary artery bypass grafting, cardiac ischemic time, ACP time >30 minutes, and year of operation.

RESULTS

Operative Mortality

In our analysis of the subcohort comprising the 891 patients in the axillary and innominate groups, the 2 groups showed no difference in operative death (7.2% vs 5.6%, *P* = .413) (Table 2). Similar results were found in the propensity-matched analysis (282 pairs), where the 2 groups showed no difference in operative death (axillary vs innominate, 4.3% [n = 12] vs 7.4% [n = 21]; *P* = .150). When we then excluded the patients with neurologic events (overall stroke) from the operative mortality category, the propensity-matched patients continued to show no difference in operative mortality.

In our analysis of the entire cohort, operative mortality was found to be 7.0% (n = 66) overall, 7.2% (n = 37) for the axillary cannulation group, and 5.6% (n = 21) for the innominate cannulation group (Table E2). Mortality was greatest among the patients who underwent femoral artery cannulation (30.8%; n = 4).

In the multivariable analysis of the axillary/innominate subcohort (Table 3), neither axillary nor innominate artery cannulation was significantly associated with operative death. The same results were found for the entire cohort (Table E3). Predictors of operative mortality for the axillary/innominate subcohort were prolonged CPB time (odds ratio [OR], 1.015; 95% confidence interval [CI], 1.01-1.02; *P* < .001), preoperative pulmonary history (OR, 2.564; 95% CI, 1.343-4.853; *P* = .004), patient age (OR, 1.103; 95% CI, 1.068-1.143; *P* < .001), full arch procedure (OR, 3.794; 95% CI, 1.991-7.31, *P* < .001), and New York Heart Association class III or IV (OR, 2.811; 95% CI, 1.504-5.265, *P* = .001) (Table 3). The predictors of mortality for the entire cohort were similar, with a few small differences (prolonged ACP time was a predictor instead of the full arch procedure) (Table E3).

TABLE 3. Multivariable regression analysis of the axillary/innominate subcohort

Outcome variable	*P* value	Odds ratio	95% Confidence interval	
Operative death				
Full arch	<.001	3.794	1.991	7.310
NYHA class III or IV	.001	2.811	1.504	5.265
Pulmonary history	.004	2.564	1.343	4.853
Age, y	<.001	1.103	1.068	1.143
CPB time, min	<.001	1.015	1.01	1.02
C index 0.877				
HL test *P* value .9				
Stroke, persistent				
Renal history	.006	7.498	1.497	29.308
Cerebrovascular history	.002	3.374	1.522	7.130
ACP time >30 min	.003	3.842	1.648	9.690
C index 0.793				
HL test *P* value 1.0				
Overall stroke				
Renal history	.017	5.738	1.146	21.585
Cerebrovascular history	.002	3.374	1.522	7.130
ACP time >30 min	.031	2.182	1.073	4.494
C index 0.709				
HL test *P* value 1.0				
Renal failure necessitating hemodialysis, persistent				
CPB time, min	<.001	1.016	1.009	1.024
C index 0.797				
HL test *P* value .5				
Bleeding requiring operation				
No variables found to be significant.				
C index 0.64				
HL test *P* value 1.0				
Respiratory failure				
Full arch	<.001	2.198	1.467	3.290
Tobacco use, current or past	.008	1.637	1.143	2.362
Aortic dissection	.028	1.595	1.049	2.414
CPB time, min	<.001	1.01	1.006	1.013
Year of operation	.004	0.919	0.867	0.974
C index 0.759				
HL test *P* value .5				
Composite adverse event				
Renal history	.022	4.439	1.212	16.009
ACP time >30 min	.035	2.246	1.047	4.725
NYHA class III or IV	.006	2.121	1.236	3.615
Cerebrovascular history	.018	2.106	1.116	3.867
Pulmonary history	.020	1.934	1.101	3.351
Age, y	<.001	1.068	1.042	1.097
CPB time, min	<.001	1.01	1.006	1.015
C index 0.848				
HL test *P* value 1.0				

NYHA, New York Heart Association; *CPB*, cardiopulmonary bypass; *HL*, Hosmer–Lemeshow; *ACP*, antegrade cerebral perfusion.

Neurologic Outcomes

Of the 938 patients in the entire cohort, 27 (2.9%) suffered persistent stroke (Table E2). The majority (n = 25) of the persistent strokes were embolic (17 axillary, 6 innominate, 1 femoral/left-side distribution, 1 direct aortic/left-side distribution), and 2 were hemorrhagic (1 axillary, 1 innominate). Femoral cannulation was associated with overall stoke (*P* = .023) in the multivariable analysis of the entire cohort of patients, but the femoral cannulation group was too small to draw conclusions from (Table E3).

Of the 891 patients in the axillary/innominate subcohort, 25 (2.8%) suffered persistent stroke; these included 18 (3.5%) of the patients in the axillary cannulation group and 7 (1.9%) of the patients in the innominate cannulation group (Table 2). Of the 23 embolic strokes that occurred, 7 had a right-side-only distribution (axillary = 6, innominate = 1), 10 had a left-side-only distribution (axillary = 7, innominate = 3), and 6 had a bilateral distribution (axillary = 4, innominate = 2).

In the multivariable analysis of the subcohort comprising the 2 main cannulation strategies (axillary and innominate), neither axillary nor innominate cannulation independently predicted stroke (Table 3). Similarly, in the analysis of the propensity-matched patients, the 2 groups showed no significant difference in overall stroke rate, with the axillary cannulation group having only a slightly greater rate than the innominate cannulation group (4.6% [n = 13] vs 2.8% [n = 8], $P = .383$) (Table 2).

Independent predictors of persistent stroke for both the entire cohort (n = 938 patients) and the axillary/innominate subcohort (n = 891 patients) were previous history of cerebrovascular disease, previous renal history, and ACP time >30 minutes (Table E3 and Table 3).

Local Injury

The cannulated vessel was not directly injured in any case. No patient who underwent right axillary cannulation had permanent brachial plexus injury.

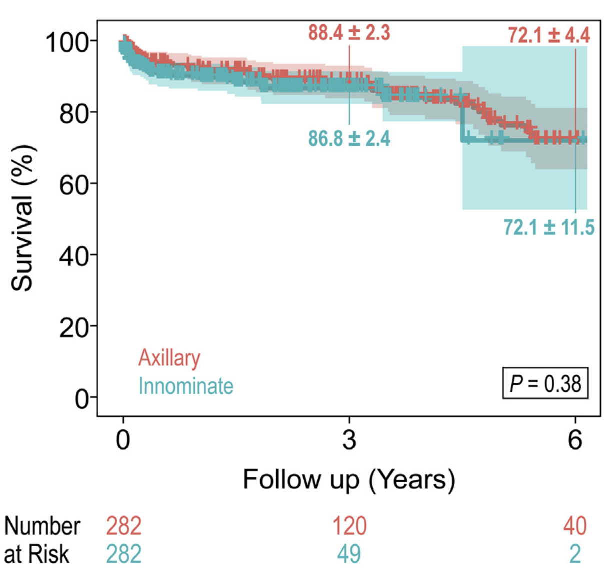

FIGURE 2. Kaplan–Meier survival *curves* for propensity-matched patients who underwent axillary or innominate artery cannulation.

Follow-up

The median follow-up period was 2.3 [interquartile range, 1.1-4.0] years (range, 30 days to 11.2 years) for the surviving patients with 30-day follow-up data available (n = 728 for the overall group). Kaplan–Meier curves showed no difference in long-term survival between the matched axillary and innominate cannulation groups (Figure 2): Survival rates were 92.1% (standard error [SE], 0.019; CI, 0.875-0.950) for the axillary group versus 89.7% (SE, 0.019; CI, 0.852-0.929) for the innominate group at 1 year and 72.1% (SE, 0.044; CI, 0.6325-0.797) versus 72.1% (SE, 0.115; CI, 0.427-0.882) at 6 years ($P = .378$).

DISCUSSION

Unilateral or bilateral ACP, in conjunction with hypothermic circulatory arrest, is used in aortic surgery to safely extend the period of circulatory arrest and facilitate complex arch procedures.[8-14] To facilitate ACP delivery, different cannulation strategies have been implemented.[1,3-6,15-21] In this study, we evaluated our experience with various cannulation strategies in patients who underwent elective proximal and total arch surgery during the past decade.

The mortality rates associated with using the 2 most common cannulation sites—the axillary and innominate arteries—did not differ significantly in the analysis of the entire cohort or in that of the smaller subcohort comprising only the axillary and innominate cannulation patients. The same results were confirmed in the analysis of the propensity-matched subgroups ($P = .150$). The mortality rate observed in our femoral cannulation group was probably high because of that group's small size and because the femoral artery was our emergent bailout cannulation site during redo sternotomy when bleeding was encountered on sternal entry (Figure 1). It is also possible that the bleeding upon sternal entry could have caused these patients to become hypotensive, which could have contributed to the greater incidence of stroke seen in the group that underwent femoral cannulation. An embolic event due to retrograde flow to the cerebral circulation with femoral arterial inflow is possible as well. Our mortality rates of 7.0% and 7.2% for the entire cohort and the axillary cannulation group, respectively, are close to the 8.4% rate (7.0% for axillary cannulation via a side graft, 7.8% for direct axillary cannulation) reported by Svensson and colleagues[20] and the 4.6% rate reported by Etz and colleagues.[17] Both of these studies included emergency and elective cases, and both associated femoral cannulation with greater mortality than the use of other cannulation sites, as in our study. Other groups have reported outstanding results with femoral artery cannulation.[22] The group from Emory reported a greater operative mortality rate (10.7%) in 122 elective cases, probably because they all were total arch procedures.[23] This group uses right axillary artery cannulation with an 8-mm side graft.

Axillary and innominate artery cannulation were not independently associated with overall or persistent stroke in either multivariable analysis, and the propensity-matching analysis confirmed these results. Although the 2 groups showed similar rates of persistent stroke in our propensity-matching analysis ($P = .791$), the rate was slightly greater in the axillary group. In contrast, Chu and colleagues[16] from Canada found that neurologic events were more frequent in their innominate cannulation group (66 patients) than in their axillary cannulation group (74 patients), but the difference was not statistically significant. In that review of 140 patients who underwent a hemiarch procedure, the reported stroke rates for the innominate cannulation and axillary cannulation groups were 3.0% and 1.4%, respectively. It should be noted that in that study, the innominate artery was cannulated directly and the axillary artery was cannulated via a side graft.

We noticed a greater stroke rate in our axillary cannulation group, but our cohort included patients who underwent total arch operations, and approximately one third underwent redo procedures. Most strokes that occur during aortic arch repair are embolic, and specific characteristics of the patient's aortic disease, such as having a heavily atheromatous aortic arch, may mediate the association between stroke rate and specific cannulation strategies. For this reason, we avoid cannulating the innominate artery if we believe that it is involved with heavy atheroma.

In addition, our propensity-matching analysis showed that the patients in the axillary group had more respiratory complications than those in the innominate group ($P = .067$), which agrees with the results of others.[16] In our multivariable analysis of the axillary/innominate subcohort, cannulation site was not found to be an independent predictor of respiratory failure. Although it was not assessed in this study, our experience suggests that patients undergoing complicated procedures with a prolonged CPB time suffer more coagulopathy, receive more products, and end up on a ventilator more often.

Regarding the technical aspects of cannulation, different groups have compared the results of direct axillary or innominate cannulation versus using a side graft.[4,6,16,20] Although some have associated direct axillary cannulation with stroke,[20] others have reported excellent results.[4] In our practice, we use an 8- or 10-mm Gelweave side graft (Vascutek Ltd, Renfrewshire, Scotland, United Kingdom) and apply a partial occluding clamp to the vessel because we find it easier. We avoid blindly placing wires or using sequential dilators in the innominate artery, because this increases stroke risk even if the intended arterial inflow cannula is small. For a heavily atherosclerotic arch with excessive atheroma, we prefer to use the right axillary artery (Figure 1).

Study Limitations

The comparisons made in this study were inherently limited by the differences in surgical year, despite the various statistical analyses performed (multivariable and propensity-matching). Also, our study was limited by its retrospective design and the inherent biases thereof. Our surgical technique underwent modifications during the study period; the recent trend has been to use innominate artery cannulation and bilateral ACP for most procedures (regardless of complexity), but there was not a specific cutoff date for this change.

Furthermore, although the 2 main groups (axillary and innominate cannulation) were large, our group sizes for the other cannulation sites were relatively small. To show the various cannulation strategies available while also providing an in-depth analysis of the 2 most common strategies, we performed 2 multivariable analyses: 1 for the entire cohort and 1 for a smaller subcohort that included only the axillary and innominate cannulation patients. In addition, we do not know exactly how many patients experienced temporary tingling in the right arm due to axillary surgical dissection, but this always resolved after a few days.

CONCLUSIONS

Different cannulation strategies can be used to establish arterial inflow for elective proximal and total arch cases. Our multivariable analysis confirmed the results of our propensity-matching analysis, which led us to believe that innominate and right axillary cannulation in elective arch surgery provide similar neuroprotection and are interchangeable, depending on the circumstances. The other cannulation strategies, although less popular, are useful in selected cases in which the innominate and right axillary sites cannot be used.

Conflict of Interest Statement

Dr Preventza consults for Medtronic, Inc, and W. L. Gore & Associates. Previously, she has received travel expenses from both Cook, Inc, and Gore. Dr Coselli consults for, receives royalties and a departmental educational grant from, and participates in clinical trials for Vascutek Terumo. Dr LeMaire participates in clinical trials for Medtronic, Inc, W. L. Gore & Associates, and Vascutek Terumo. All other authors have nothing to disclose with regard to commercial support.

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Key Words: axillary artery cannulation, innominate artery cannulation, arch surgery, cannulation, neurologic outcomes, circulatory arrest

TABLE E1. Preoperative characteristics, demographics, and intraoperative details of the entire cohort

Characteristics	Overall (n = 938)	Axillary (n = 515)	Innominate (n = 376)	Direct aortic (n = 19)	Carotid (n = 15)	Femoral (n = 13)	P value
Age, y	60.6 ± 13.7	61.3 ± 13.6	59.5 ± 14.0	62.4 ± 9.1	63.9 ± 8.2	59.8 ± 16.3	.268
Male	644 (68.7)	352 (68.4)	259 (68.9)	14 (73.7)	12 (80.0)	7 (53.9)	.649
Confirmed or suspected genetic disease	99 (10.6)	49 (9.5)	45 (12.0)	1 (5.3)	2 (13.3)	2 (15.4)	.584
Aortic aneurysm without dissection	707 (75.4)	346 (67.2)	334 (88.8)	16 (84.2)	8 (53.3)	3 (23.1)	<.001
Aortic dissection	231 (24.6)	169 (32.8)	42 (11.1)	3 (5.3)	7 (46.7)	10 (76.9)	<.001
Hypertension	806 (85.9)	439 (85.2)	326 (86.7)	18 (94.7)	14 (93.3)	9 (69.2)	.314
Diabetes	80 (8.5)	40 (7.8)	37 (9.8)	2 (10.5)	1 (6.7)	0 (0)	.684
Tobacco use, current or past	531 (56.6)	304 (59.0)	201 (53.5)	10 (52.6)	10 (66.7)	6 (46.2)	.397
NYHA class III or IV	231 (24.6)	155 (30.1)	60 (16.0)	7 (36.8)	2 (13.3)	7 (53.9)	<.001
Cardiac history*	230 (24.5)	119 (23.1)	95 (25.3)	2 (10.5)	7 (46.7)	7 (53.9)	.016
Pulmonary history†	199 (21.2)	119 (23.1)	67 (17.8)	7 (36.8)	3 (20.0)	3 (23.1)	.142
Renal history‡	15 (1.6)	8 (1.6)	6 (1.6)	0 (0)	0 (0)	1 (7.7)	.457
Cerebrovascular history§	116 (12.4)	75 (14.6)	36 (9.6)	0 (0)	4 (26.7)	1 (7.7)	.024
Previous proximal aortic repair‖	191 (20.4)	145 (28.2)	31 (8.2)	1 (5.3)	5 (33.3)	9 (69.2)	<.001
Redo sternotomy	286 (30.5)	214 (41.6)	54 (14.4)	2 (10.5)	6 (40.0)	10 (76.9)	<.001
CPB time, min	144.7 ± 55.9	146.5 ± 55.9	138.1 ± 49.7	166.2 ± 95.8	162.3 ± 74.4	209.6 ± 77.8	.002
ACP time >30 min	330 (35.2)	218 (42.3)	82 (21.8)	6 (31.6)	14 (93.3)	10 (76.9)	<.001
Cardiac ischemic time, min	97.4 ± 39.6	93.1 ± 39.9	102.5 ± 38.0	93.7 ± 44.5	115.3 ± 46.2	100.4 ± 40.0	.001
ACP time, min	33.8 ± 25.6	37.4 ± 27.6	27.5 ± 20.0	26.4 ± 23.2	65.5 ± 28.8	49.2 ± 26.9	<.001
ACP, unilateral	319 (34.0)	271 (52.6)	26 (6.9)	14 (73.7)	3 (20.0)	5 (38.5)	<.001
ACP, bilateral	619 (66.0)	244 (47.4)	350 (93.1)	5 (26.3)	12 (80.0)	8 (61.5)	<.001
Full arch	242 (25.8)	168 (32.6)	52 (13.8)	7 (36.8)	11 (73.3)	4 (30.8)	<.001
Hemiarch	696 (74.2)	347 (67.4)	324 (86.2)	12 (63.2)	4 (26.7)	9 (69.2)	<.001
Concomitant aortic root repair or replacement¶	303 (32.3)	118 (22.9)	176 (46.8)	6 (31.6)	2 (13.3)	1 (7.7)	<.001
Concomitant aortic valve replacement#	266 (28.4)	147 (28.5)	107 (28.5)	6 (31.6)	3 (20.0)	3 (23.1)	.938
Concomitant CABG**	152 (16.2)	90 (17.5)	58 (15.4)	1 (5.3)	2 (13.3)	1 (7.7)	.641

Data are presented as mean ± standard deviation for continuous variables and n (%) for categorical variables. *NYHA*, New York Heart Association; *CPB*, cardiopulmonary bypass; *ACP*, antegrade cerebral perfusion; *CABG*, coronary artery bypass grafting. *History of angina, myocardial infarction, CABG, percutaneous transluminal coronary angiography/stenting, or arrhythmia/heart block. †History of asthma or chronic obstructive pulmonary disease. ‡Initial serum creatinine level ≥3.0 mg/dL, renal failure necessitating hemodialysis, or renal insufficiency. §History of transient ischemic attack, stroke, carotid endarterectomy, or cerebral aneurysm. ‖Previous ascending aortic repair or aortic root replacement. ¶Aortic valve-sparing; composite valve graft, tissue or mechanical; homograft; or stentless tissue. #Tissue or mechanical. **1, 2, 3, or 4 vessels.

TABLE E2. Short-term complications of the entire cohort

Complication	Overall (n = 938)	Axillary (n = 515)	Innominate (n = 376)	Direct aortic (n = 19)	Carotid (n = 15)	Femoral (n = 13)	*P* value
Operative death*	66 (7.0)	37 (7.2)	21 (5.6)	2 (10.5)	2 (13.3)	4 (30.8)	.008
Stroke, persistent	27 (2.9)	18 (3.5)	7 (1.9)	1 (5.3)	0 (0)	1 (7.7)	.233
Overall stroke†	38 (4.1)	25 (4.9)	9 (2.4)	1 (5.3)	0 (0)	3 (23.1)	.014
Composite adverse event‡	92 (9.8)	55 (10.7)	26 (6.9)	3 (15.8)	4 (26.7)	4 (30.8)	.003
Renal dysfunction/insufficiency	75 (8.0)	43 (8.4)	22 (5.9)	3 (15.8)	0 (0)	7 (53.9)	<.001
Renal failure necessitating hemodialysis							
Transient	15 (1.6)	9 (1.8)	5 (1.3)	1 (5.3)	0 (0)	0 (0)	.560
Permanent	34 (3.6)	21 (4.1)	10 (2.7)	1 (5.3)	1 (6.7)	1 (7.7)	.277
Respiratory failure	224 (23.9)	143 (27.8)	57 (15.2)	8 (42.1)	6 (40.0)	10 (76.9)	<.001
Tracheostomy	79 (8.4)	53 (10.3)	19 (5.1)	3 (15.8)	2 (13.3)	2 (15.4)	.010
Heart block requiring pacemaker	66 (7.1)	38 (7.4)	23 (6.1)	3 (15.8)	1 (6.7)	1 (7.7)	.397
Bleeding requiring operation	30 (3.2)	20 (3.9)	7 (1.9)	0 (0)	0 (0)	3 (23.1)	.013

Data are presented as n (%). *Intraoperative, 30-day, or in-hospital death. †Persistent or transient stroke. ‡Operative death, persistent stroke, persistent renal failure necessitating hemodialysis, or persistent paraparesis/paraplegia.

TABLE E3. Multivariable regression analysis of the entire cohort

Outcome variable	*P* value	Odds ratio	95% Confidence interval	
Operative death				
ACP time >30 min	<.001	2.960	1.595	5.631
Pulmonary history	.001	2.609	1.439	4.703
NYHA class III and IV	.018	2.004	1.12	3.556
Age, y	<.001	1.092	1.06	1.128
CPB time, min	<.001	1.013	1.009	1.018
C index 0.858				
HL test *P* value .2				
Stroke, persistent				
Renal history	.004	8.088	1.613	30.928
Cerebrovascular history	<.001	4.563	1.962	10.246
ACP time >30 min	.004	3.335	1.489	7.976
C index 0.753				
HL test *P* value 1.0				
Overall stroke				
Cannulation site (ref. axillary)				
Femoral	.023	5.343	1.063	20.732
Renal history	.003	7.671	1.826	27.151
Cerebrovascular history	.001	3.645	1.673	7.623
C index 0.683				
HL test *P* value .7				
Renal failure necessitating dialysis, persistent				
NYHA class III and IV	.003	3.196	1.502	6.905
Pulmonary history	.015	2.661	1.193	5.852
Full arch	.044	2.241	1.016	4.939
Age, y	<.001	1.098	1.055	1.147
CPB time, min	<.001	1.011	1.006	1.017
C index 0.877				
HL test *P* value .8				
Bleeding requiring operation				
Cannulation site (ref. axillary)				
Femoral	.009	6.473	1.334	24.299
C index 0.685				
HL test *P* value 1.0				
Respiratory failure				
Cannulation site (ref. axillary)				
Femoral	.007	7.174	1.872	36.14
Full arch	<.001	2.119	1.458	3.08
Tobacco use, current or past	.01	1.586	1.122	2.26
Redo sternotomy	.037	1.515	1.024	2.23
Age, y	<.001	1.033	1.018	1.05
CPB time, min	<.001	1.009	1.006	1.01
C index 0.768				
HL test *P* value .4				

(Continued)

TABLE E3. Continued

Outcome variable	*P* value	Odds ratio	95% Confidence interval	
Composite adverse event				
ACP time >30 min	<.001	2.883	1.648	5.120
Cerebrovascular history	.015	2.059	1.133	3.652
Pulmonary history	.016	1.890	1.115	3.166
NYHA class III and IV	.018	1.827	1.10.1	3.007
Aortic dissection	.033	1.783	1.045	3.033
Age, y	<.001	1.059	1.035	1.086
CPB time, min	<.001	1.011	1.007	1.015
Composite root replacement	.131	0.582	0.282	1.151
C index 0.837				
HL test *P* value 1.0				

ACP, Antegrade cerebral perfusion; *NYHA*, New York Heart Association; *CPB*, cardiopulmonary bypass; *HL*, Hosmer–Lemeshow.