Developing skills for thoracic aortic surgery with hypothermic circulatory arrest

Amine Mazine, MD, MSc,^a Louis-Mathieu Stevens, MD, PhD, FRCSC,^b Aly Ghoneim, MD,^c Jennifer Chung, MD, MSc, FRCSC,^d Maral Ouzounian, MD, PhD, FRCSC,^d Francois Dagenais, MD, FRCSC,^e Ismail El-Hamamsy, MD, PhD, FRCSC,^c Munir Boodhwani, MD, MMSc, FRCSC,^f John Bozinovski, MD, MSc, FRCSC,^g Mark D. Peterson, MD, PhD, FRCSC,^h and Michael W. A. Chu, MD, FRCSC,ⁱ the Canadian Thoracic Aortic Collaborative Investigators

ABSTRACT

Objectives: To examine the performance curves of 8 early-career aortic surgeons with the use of hypothermic circulatory arrest (HCA) and to analyze the impact of the learning curve on perioperative outcomes.

Methods: A total of 1025 consecutive patients who underwent aortic reconstruction with HCA between 2002 and 2017 were analyzed for mortality and 5 other complications (stroke, reoperation for bleeding, dialysis, prolonged ventilation, and sternal wound complications), subdivided into 3 consecutive time periods. This cohort represents the complete inaugural experience of 8 Canadian academic aortic surgeons. A risk-adjusted cumulative sum analysis was used to evaluate the performance curve with respect to predetermined 80% alert and 95% alarm boundary lines.

Results: Mean age was 62 ± 13 years, 71% of patients were male, and 24% presented nonelectively. Hemiarth repair was performed in 80% and total arch replacement in 20%. There was a reduction in the incidence of the primary composite outcome over time (P1: 26%, P2: 23%, and P3: 16%; $P = .010$). Overall in-hospital mortality was 5% and remained stable throughout the 3 periods. Rates of stroke were lower in the late period (P1: 4%, P2: 6%, and P3: 2%; $P = .035$). Risk-adjusted cumulative sum analysis demonstrated that all surgeons remained within the 95% reassurance boundary throughout their experience, with 6 surgeons performing as expected and 2 performing better than expected.

Conclusions: Early-career surgeons can safely perform operations with HCA from the initiation of their practice. The cumulative sum analysis method is valuable for monitoring competence in aortic surgery and could prove useful in structuring training programs. (J Thorac Cardiovasc Surg 2019;157:1360-8)

Early-career surgeons can safely perform aortic arch repair with circulatory arrest with good outcomes. Graphical abstract presenting characteristics of the study cohort and results of the CUSUM analysis.

Central Message

Early-career surgeons can safely perform aortic operations with hypothermic circulatory arrest from the initiation of their practice. The CUSUM analysis method is valuable for monitoring competence in aortic surgery.

Perspective

Several studies have investigated the relationship between institutional volumes and outcomes following aortic surgery. However, few have examined individual surgeons' performance. We found variability in the performance curves of 8 early-career surgeons performing operations with hypothermic circulatory arrest. However, all surgeons remained within the 95% reassurance boundary throughout their experience.

See Commentary on page 1369.

From the ^aDivision of Cardiac Surgery, Department of Surgery, University of Toronto, Toronto, Ontario, Canada; ^bDivision of Cardiac Surgery, Department of Surgery, Centre Hospitalier Universitaire de Montréal and Université de Montréal, Montreal, Quebec, Canada; ^cDivision of Cardiac Surgery, Department of Surgery, Montreal Heart Institute and Université de Montréal, Montreal, Quebec, Canada; ^dDivision of Cardiac Surgery, Department of Surgery, Toronto General Hospital and University of Toronto, Toronto, Ontario, Canada; ^eDivision of Cardiac Surgery, Department of Surgery, Institut universitaire de cardiologie et de pneumologie de Québec and Université Laval, Quebec City, Quebec, Canada; ^fDivision of Cardiac Surgery, Department of Surgery, Ottawa Heart Institute and University of Ottawa, Ottawa, Ontario, Canada; ^gDivision of Cardiac Surgery, Department of Surgery, Royal Jubilee Hospital and University of British Columbia, Victoria, British Columbia, Canada; ^hDivision of Cardiac Surgery, Department of Surgery, St Michael's Hospital and University of Toronto, Toronto, Ontario, Canada; and ⁱDivision of Cardiac Surgery, Department of Surgery, London Health Sciences Center and University of Western Ontario, London, Ontario, Canada.

Read at The American Association for Thoracic Surgery Aortic Symposium 2018, New York, New York, April 26-27, 2018.

Received for publication May 10, 2018; revisions received Nov 13, 2018; accepted for publication Nov 22, 2018; available ahead of print Jan 18, 2019.

Address for reprints: Michael W.A. Chu, MD, FRCSC, Division of Cardiac Surgery, Department of Surgery, University of Western Ontario, London Health Sciences Center, P.O. Box 5339, 339 Windermere Rd, B6-106 University Hospital, London, Ontario N6A 5A5, Canada (E-mail: michael.chu@lhsc.on.ca). 0022-5223/\$36.00

Copyright © 2018 by The American Association for Thoracic Surgery <https://doi.org/10.1016/j.jtcvs.2018.11.110>

Abbreviations and Acronyms

ACP	= antegrade cerebral perfusion
CUSUM	= cumulative sum
HCA	= hypothermic circulatory arrest

Scanning this QR code will take you to the article title page to access supplementary information. To view the AATS Aortic Symposium Webcast, see the URL next to the webcast thumbnail.

Deep hypothermia with circulatory arrest was introduced in the 1970s¹ and remains the approach of choice for a variety of aortic procedures. Although operations performed with the use of hypothermic circulatory arrest (HCA) span a broad spectrum of complexity, it is widely held that these procedures are technically demanding and associated with increased surgical risk. One of the main potential drawbacks for adopting any complex operation is the inherent learning curve. In this age of increased scrutiny and individual surgeon reporting, the issue of the learning curve is of great relevance, especially for early-career surgeons. Quality control metrics of nationally published databases focus heavily on perioperative outcomes. This raises questions about the feasibility and safety of starting an HCA program, particularly for surgeons in the early stages of their practice.

Several studies have investigated the relationship between institutional volumes and outcomes following aortic surgery, demonstrating an association between greater volumes and improved outcomes.²⁻⁴ However, few have examined individual surgeons' performance. Herein, we analyze the performance of 8 early-career aortic surgeons with the use of HCA across a spectrum of aortic reconstructive procedures. The aim of this study was to analyze the impact of the learning curve on short-term outcomes following aortic operations requiring HCA.

METHODS

Study Population

Between May 2002 and November 2017, a total of 1025 consecutive patients (mean age 62 ± 13 years) underwent surgery with the use of HCA across 7 centers participating in the Canadian Thoracic Aortic Collaborative. This cohort represents the inaugural experience of 8 academic aortic surgeons who started their respective aortic practices between 2002 and 2014. Patients who underwent thoracoabdominal aortic aneurysm repair were excluded from the present analysis. Cases were performed independently from one operator to another, such that the individual performance curves are not transposable. The total number of aortic cases performed yearly with HCA by each surgeon is presented in [Figure 1](#). The study was approved by the local ethics committee at each institution, and a waiver of consent was obtained.

Outcomes and Data Analysis

Baseline characteristics, surgical details, and early outcomes were retrospectively collected through chart review using a standardized data collection form. The primary safety outcome was a composite endpoint that included death and 5 other perioperative adverse events: stroke, bleeding requiring re-exploration, acute renal failure requiring dialysis, long duration of postoperative mechanical ventilation (>40 hours), and mediastinitis/sternal dehiscence. In addition, other adverse events (eg, myocardial infarction, atrial fibrillation, spinal cord injury, septic shock), blood product transfusion, as well as intensive care unit and hospital lengths of stay were analyzed as secondary outcomes.

Risk-adjusted cumulative sum (CUSUM) analyses were used to assess individual surgeon performance with respect to the primary safety outcome. Subgroup analyses were performed to compare the performance curves for hemiarch replacement versus total arch replacement, as well as for elective versus nonelective surgery. In addition, temporal trends for the occurrence of the primary safety outcome and secondary outcomes were analyzed by chronologically dividing each surgeon's cohort into thirds (ie, total number of cases divided by 3), and then pooling these thirds together. As such, each surgeon's learning experience is evenly proportioned within all 3 periodic groups.

Statistical Analysis

Continuous variables are expressed as mean $\pm$ standard deviation or median [interquartile range] and were compared using analysis of variance with a log transformation for non-normally distributed variables. Categorical variables are expressed as frequencies (%) and were compared using the Pearson χ^2 test or Fisher's exact test, as appropriate. The Tukey adjustment was used for multiple comparisons. Statistical significance was set at $\alpha = 0.05$.

Unadjusted and risk-adjusted CUSUM analyses were performed for the primary safety outcome for each surgeon using the method described by Rogers and colleagues.⁵ To summarize in brief, for each curve, acceptable (p0) and unacceptable (p1) complication rates were determined for the safety outcome. For the unadjusted curves, p0 was defined as the average incidence of the composite safety endpoint across the entire cohort. As such, "p0" was set at 32.5% for the full cohort, 30.1% for hemiarch cases, 42.3% for total arch cases, 48.0% for urgent cases, and 27.5% for elective cases. For the risk-adjusted curves, "p0" was defined as the predicted probability of incidence of the composite endpoint. This predicted probability was calculated for each patient using a multivariable logistic regression model ([Table E1](#)). Least absolute shrinkage and selection operator selection methods were used to identify candidate variables for the multivariable model.⁶ For all adjusted and unadjusted curves, "p1" was calculated by setting the odds ratio between "p0" and "p1" at 1.5 (50% increase in the odds ratio).

Using the aforementioned method, "p1" is static for unadjusted curves but variable for risk-adjusted curves, hence the need to present data on the log-likelihood scale. As such, cumulative log-likelihood ratio test charts and risk-adjusted sequential probability ratio test charts were used to present unadjusted and risk-adjusted CUSUM curves, respectively. In both cases, crossing of the upper boundary demonstrated a failure rate significantly greater than the unacceptable rate (p1) (ie, surgeon performing worse than expected), whereas a CUSUM curve inferior to the lower boundary indicated a failure rate lower than the acceptable rate (p0) (ie, surgeon performing better than expected). A CUSUM curve between the 2 boundaries was indicative of a lack of statistical significance (ie, surgeon performing as expected). Statistical analyses were performed using SAS 9.4 (SAS Institute, Cary, NC).

RESULTS

Baseline Characteristics

Baseline patient characteristics are summarized in [Table 1](#). In general, baseline patient characteristics

FIGURE 1. Distribution of cases performed by each surgeon over time.

remained stable throughout the study period (Table E2). Chronic obstructive pulmonary disease was less prevalent in the late period ($P = .028$). There was a greater proportion of patients presenting with aortic aneurysms ($P = .005$) and, reciprocally, a lower proportion presenting with aortic dissection ($P = .013$) during the late period. Patients underwent surgery at a slightly lower mean aortic diameter during the intermediate and late periods. The prevalence of concomitant aortic insufficiency was greater during the late period ($P < .001$). Overall, 151 patients (15%) had undergone previous cardiac surgery. A bicuspid aortic valve was present in 321 patients (32%). A greater proportion of patients presented electively during the late period as compared with the early period ($P = .044$). Differences in baseline characteristics between patients operated by each of the 8 participating surgeons are presented in Table E3.

Operative Details

Operative details are presented in Table 2. There were significant changes over time (Table E4). Concomitant aortic valve replacement ($P = .045$) and valve-sparing root replacement ($P = .005$) were performed more frequently in the late period. Cannulation and perfusion strategies evolved over time. Axillary cannulation was performed less frequently in the later part of the experience, in favor of innominate artery cannulation ($P < .001$). Surgeons were also more likely to perfuse through an elephant trunk graft in the intermediate and late periods, as compared with the early period ($P < .001$). There was a temporal trend toward lesser degrees of hypothermia over

time with a median nadir HCA temperature of 20°C in the early period versus 25°C in the intermediate and late periods ($P < .001$). Selective antegrade cerebral perfusion (ACP) was commonly used by 7 surgeons from the onset of their experience and routinely by all 8 surgeons in the late period. There was a decrease in the median duration of HCA in the late period, as compared with the early period ($P = .029$). Differences in operative details between patients operated by each of the 8 participating surgeons are presented in Table E5.

Perioperative Outcomes

Perioperative outcomes are presented for the entire cohort in Table 3, and for each period in Table E6. Overall in-hospital mortality was 5% and remained stable throughout all 3 time periods. With growing experience, there was a reduction in the incidence of the primary outcome (ie, ≥ 1 major complications) from 26% in the early period to 23% in the intermediate period to 16% in the late period ($P = .010$). This reduction was primarily driven by lower rates of stroke ($P = .035$) and prolonged mechanical ventilation ($P = .001$) in the late period. No difference was observed for the incidence of the 4 other complications that composed the primary safety outcome. Analysis of secondary endpoints revealed reductions in the rates of postoperative atrial fibrillation ($P = .017$), transient ischemic attack ($P = .034$), and delirium ($P = .005$). With increasing experience, there was also a reduction in the use of all blood products. Median intensive care unit ($P = .002$) and hospital ($P = .006$) lengths of stay were shorter in the late period. Differences in perioperative

TABLE 1. Baseline patient characteristics

	Total (n = 1025)
Age, y, mean $\pm$ SD	62 $\pm$ 13
Female sex	301 (29%)
Body mass index, kg/m ² , mean $\pm$ SD	28 $\pm$ 5
NYHA class III or IV	244 (24%)
LVEF <40%	60 (6%)
Previous cardiac surgery	151 (15%)
Risk factors, (%)	
Smoking	408 (40)
Hypertension	710 (69)
Diabetes mellitus	114 (11)
Dyslipidemia	501 (49)
Comorbidities, (%)	
Coronary artery disease	222 (22)
Previous myocardial infarction	72 (7)
Congestive heart failure	92 (10)
Atrial fibrillation	136 (13)
Peripheral vascular disease	100 (10)
History of stroke	52 (5)
History of TIA	47 (5)
Any cerebrovascular disease	102 (10)
History of chronic renal disease	103 (10)
COPD	127 (12)
Connective tissue disorder*	45 (4)
Thoracic aortic pathology, (%)†	
Aortic aneurysm	900 (88)
Aortic dissection	228 (22)
Aortic rupture	32 (3)
Maximum aortic diameter, mm, mean $\pm$ SD	55 $\pm$ 10
Aortic valve pathology, (%)‡	
Aortic stenosis	288 (28)
Aortic insufficiency‡	200 (20)
Morphology	
Tricuspid	680 (67)
Bicuspid	321 (32)
Unicuspid	12 (1)
Presentation status, (%)	
Elective	773 (75)
Urgent	83 (8)
Emergent	155 (15)
Salvage	14 (1)

SD, Standard deviation; NYHA, New York Heart Association; LVEF, left ventricular ejection fraction; TIA, transient ischemic attack; COPD, chronic obstructive pulmonary disease. *Genetically confirmed. †Not mutually exclusive. ‡Greater than mild.

outcomes between patients operated by each of the 8 participating surgeons are presented in Table E7.

CUSUM Analyses of Safety Outcomes

The mean number of aortic cases with HCA performed per surgeon per year—starting with the first complete year in practice—was 14 and ranged from 9 to 26. CUSUM analysis showed variability in the performance curves of the 8 participating surgeons (Figure 2). Unadjusted curves

TABLE 2. Operative details

	Total (n = 1025)
Thoracic aortic procedure, (%)*	
Hemiarch replacement	818 (80)
Total arch replacement	201 (20)
Elephant trunk	134 (13)
Aortic valve and/or root procedure, (%)*	
Aortic valve replacement	178 (17)
Biological	129 (13)
Mechanical	49 (5)
Bentall procedure	333 (32)
Biological	199 (19)
Mechanical	134 (13)
Aortic valve repair	199 (19)
Valve-sparing root replacement	124 (12)
Ross procedure	33 (3)
Sinus root repair	80 (8)
Concomitant procedures, (%)*	
CABG	203 (20)
Mitral valve repair	25 (2)
Mitral valve replacement	13 (1)
ASD/VSD repair	12 (1)
Other concomitant procedures	89 (8)
Arterial cannulation, (%)*	
Femoral	64 (6)
Axillary	550 (54)
Innominate	311 (30)
Carotid	7 (1)
Distal arch	157 (15)
Elephant trunk graft	125 (12)
Perfusion details	
CPB time, min, median [IQR]	166 [127, 220]
Aortic crossclamp time, min, median [IQR]	117 [79, 163]
HCA duration, min, median [IQR]	20 [13, 29]
Long HCA duration (>40 min)	145 (14%)
HCA lowest temperature, °C, median [IQR]	24 [20, 26]
Cerebral perfusion, (%)	
None	98 (10)
Antegrade	909 (89)
Retrograde	18 (2)

CABG, Coronary artery bypass grafting; ASD, atrial septal defect; VSD, ventricular septal defect; CPB, cardiopulmonary bypass; IQR, interquartile range; HCA, hypothermic circulatory arrest. *Not mutually exclusive.

(Figure 2, A) demonstrated that 5 of 8 surgeons remained between the reassurance and alarm boundaries throughout their experience (ie, performed as expected), 2 surgeons eventually crossed the 95% reassurance boundary line (ie, performed better than expected), whereas 1 surgeon persistently remained above the 95% alert boundary line (ie, performed worse than expected). However, when we adjusted for baseline patient characteristics, all surgeons remained within the 95% reassurance boundary throughout their experience, with 6 surgeons performing as expected and 2 performing better than expected (Figure 2, B). Among surgeons who crossed the reassurance line, improvements

TABLE 3. Perioperative outcomes

	Total (n = 1025)
Primary safety outcome, (%)	
≥1 major complications*	221 (22)
In-hospital or 30-d mortality	54 (5)
Stroke	44 (4)
Reoperation for bleeding	87 (8)
Dialysis-dependent renal failure	36 (4)
>40 h of mechanical ventilation	107 (10)
Sternal dehiscence/mediastinitis	10 (1)
Other adverse events, (%)	
Myocardial infarction	15 (1)
Postoperative IABP requirement	2 (0)
Postoperative atrial fibrillation	375 (37)
Cardiac arrest/malignant arrhythmia	30 (3)
Spinal cord injury	9 (1)
Transient ischemic attack	18 (2)
Delirium	198 (19)
Septic shock	14 (1)
Blood product transfusion, (%)	
Packed red blood cells	352 (34)
Fresh-frozen plasma	441 (43)
Platelets	458 (45)
Factor VII	62 (6)
ICU length of stay, d, median [IQR]	2 [1, 4]
ICU length of stay ≥4 d	272 (27%)
Hospital length of stay, d, median [IQR]	7 [5, 12]

IABP, Intra-aortic balloon pump; ICU, intensive care unit; IQR, interquartile range.

*Major complications defined as the occurrence of at least 1 of the following: death, stroke, bleeding requiring re-exploration, acute renal failure requiring dialysis, long duration of postoperative mechanical ventilation (>40 hours), and sternal dehiscence/mediastinitis.

in outcomes were seen after ~50 to 70 cases. Of note, following risk adjustment, 1 of the surgeons who was performing better than expected on the unadjusted curves performed as expected, whereas a different surgeon who was performing as expected on the unadjusted analysis performed better than expected.

When considering only hemiarch repairs (with risk adjustment), findings were similar, albeit with earlier crossing of the 95% reassurance line (~50 cases) for the 2 surgeons performed better than expected (Figure 3, A). The remaining 6 surgeons performed as expected throughout their experience. In contrast, only 1 of 8 surgeons crossed the 95% reassurance line on the risk-adjusted total arch replacement CUSUM curve (Figure 3, B). Importantly, all surgeons remained within the 80% reassurance boundary throughout their experience with total arch replacement. Similarly, when stratifying by case urgency, all surgeons remained within the reassurance boundary throughout their experience with elective cases (Figure 4, A), with 2 of 8 surgeons eventually crossing the 95% reassurance boundary. Finally, for nonelective cases (Figure 4, B), only 1 of 8 surgeons crossed the 95%

FIGURE 2. Overall performance curve for aortic reconstruction with hypothermic circulatory arrest. Unadjusted (A) and risk-adjusted (B) cumulative sum plot for the occurrence of the safety outcome (any of 6 major adverse events) during aortic reconstruction with hypothermic circulatory arrest in the entire cohort. Each colored line represents a different surgeon's learning curve. Dashed lines: 80% alert (top) and reassurance (bottom) lines. Dotted lines: 95% alarm (top) and reassurance (bottom) lines.

reassurance line, whereas 1 surgeon crossed the 80% alert line. No correlation was observed between the total or annual volume of nonelective cases performed and crossing of the reassurance/alert boundary lines. However, there was a single surgeon who consistently crossed the 95% risk-adjusted reassurance line (ie, performed better than expected) across all subgroups, and this surgeon had the second-greatest annual and total case volume.

DISCUSSION

This study sought to assess the performance of early-career surgeons with the use of HCA within a comprehensive aortic program. The main findings are that HCA can be used safely in a wide variety of elective and nonelective aortic operations, including by surgeons in their first years of practice (Video 1). After we adjusted for

A

B

FIGURE 3. Learning curve for aortic reconstruction with hypothermic circulatory arrest stratified by extent of distal reconstruction. Risk-adjusted cumulative sum plot for the occurrence of the safety outcome (any of 6 major adverse events) during hemiarch replacement (A) and total arch replacement (B) with hypothermic circulatory arrest. Each colored line represents a different surgeon's learning curve. Dashed lines: 80% alert (top) and reassurance (bottom) lines. Dotted lines: 95% alarm (top) and reassurance (bottom lines).

baseline patient risk, all surgeons performed as expected or better throughout their experience. Furthermore, this analysis allowed identification of an outlier who consistently performed better than expected, across all subgroups. Despite variability in individual performance, overall mortality and morbidity in this multicenter cohort from 8 early-career surgeons compare favorably with the published literature, including results from high-volume centers with established expertise in thoracic aortic surgery.⁷⁻¹²

Although there are some differences between the programs represented in this study, a common theme is that each of the participating surgeons is supported by a well-organized, multimodal program focused on the medical and surgical management of aortic diseases (ie, comprehensive aortic program). Characteristics of such programs include rigorous follow-up of patients at regularly

A

B

FIGURE 4. Learning curve for aortic reconstruction with hypothermic circulatory arrest stratified by procedure urgency. Risk-adjusted cumulative sum plot for occurrence of the safety outcome (any of 6 major adverse events) during elective (A) and nonelective (B) aortic reconstruction with hypothermic circulatory arrest. Each colored line represents a different surgeon's learning curve. Dashed lines: 80% alert (top) and reassurance (bottom) lines. Dotted lines: 95% alarm (top) and reassurance (bottom lines).

scheduled intervals (including routine echocardiographic and computed tomography or magnetic resonance imaging), presence of a multidisciplinary aortic clinic—including geneticists, cardiologists, vascular surgeons, radiologists, etc—with a wide referral base (ie, cardiologists, general practitioners, radiologists, emergency physicians), and a therapeutic armamentarium spanning the gamut of open, endovascular, and hybrid aortic techniques. Furthermore, most of these aortic programs are not only active in clinical care but also have busy research activities. As a result, the aortic programs helped support these early-career surgeons with high volumes of carefully selected patients undergoing well-planned operations with careful patient follow-up.

All 8 surgeons participating in this study started performing operations with the use of HCA during their first year in practice, highlighting the notion that these operations can be

performed reproducibly and safely early in an aortic surgeon's career, provided that a number of conditions are met. These conditions include proper training—6 of the 8 participating surgeons had formal fellowship training in aortic surgery—adequate patient selection, satisfactory mentorship, and a sufficient volume of thoracic aortic operations. Of note, all participating surgeons practice in academic centers and were assisted by surgical trainees for the vast majority of cases. However, it is plausible that a senior, more experienced surgeon may have assisted on some of the greatest-risk cases. The correlation between surgical volumes and outcomes in cardiac surgery is now well established, particularly for thoracic aortic surgery.^{2,3,13} Hence, to mitigate the effects of the learning curve, surgeons should strive to perform a minimum number of these operations per year. In the present study, the mean number of aortic cases with HCA performed per surgeon per year—starting with the first complete year in practice—was 14 and ranged from 9 to 26. Of note, the surgeon with the best performance curve was also the one with the second-greatest mean annual volume.

Although these findings are in keeping with the expanding body of evidence linking surgical outcomes to case volume, the number of surgeons included in the present study is too low to draw any definitive conclusions. Furthermore, although there were no notable differences in the performance the 2 surgeons without formal aortic fellowship training compared with the other 6 surgeons, no meaningful conclusions can be derived from the small number of surgeons included. In addition, it should be stressed that despite risk adjustment, residual differences in baseline patient characteristics, concomitant operations, and center expertise in the management of these patients may have contributed to the differences in outcomes observed between surgeons participating in this study.

The overall operative mortality in this series was 5% (including elective and nonelective cases), which compares favorably with the published experience of established high-volume aortic centers,^{11,12} considering the fact that a high proportion of patients underwent complex concomitant procedures—such as aortic valve repair, valve-sparing root replacement, and the Ross procedure—and that a quarter of patients presented nonelectively. Despite more extensive concomitant proximal aortic surgery in the late period, operative mortality remained stable throughout the study. This may be in part explained by the fact that a greater proportion of patients presented electively during the late period. The significant improvement observed in the primary composite outcome during the later stages of the study was mainly driven by lower rates of prolonged mechanical ventilation. This finding must be interpreted in light of the fact that fewer patients had coexisting chronic obstructive pulmonary disease during the late period.

There was an evolution in cannulation and cerebral-protection strategies over the course of the study.

Specifically, with increasing experience, there was a shift toward increased use of innominate artery cannulation, more frequent use of ACP, and a move toward more moderate degrees of hypothermia, despite the increase in overall operative complexity throughout the study periods. Indeed, although hypothermia is the cornerstone of neuroprotection during aortic arch surgery, the optimal core temperature and ideal mode of cerebral perfusion remain controversial. The shift from deep HCA to moderate HCA in this study is consistent with a wider trend observed in recent years.¹⁴⁻¹⁷ This shift in practice has been driven by a desire to mitigate the potential risk of severe coagulopathy associated with deep HCA, reduce cooling and rewarming times, and improve the overall operative efficiency.

Interestingly, over the course of this study, there was a significant decrease in rates of perioperative transfusions, which coincided with the shift from deep HCA to moderate HCA. Importantly, despite this shift toward lesser degrees of hypothermia, rates of spinal ischemia remained low and constant throughout the study periods, whereas the incidence of stroke decreased in the late period. These data suggest that moderate HCA may constitute a safe and effective alternative to deep HCA. However, this study was not designed to assess the impact of HCA temperature on the incidence of perioperative blood product transfusion, and any association observed should be interpreted as hypothesis-generating. Furthermore, the potential benefits derived from using lesser degrees of hypothermia must be balanced with the extent of surgery, predicted duration of HCA, and adequate brain-protection strategies.

Another evolution in surgical strategy observed in this study was the increased use of ACP over time. This shift in practice also reflects a growing consensus in recent years toward favoring ACP over retrograde cerebral perfusion as an adjunct cerebral protection strategy.^{14,18-20} This trend has been facilitated by the increased use of axillary cannulation, which has progressively gained popularity over femoral cannulation for arterial inflow.¹⁹⁻²⁴ More recently, innominate artery cannulation has been recognized as a simplified, reproducible, and safe alternative route for ACP.^{11,25,26} The majority of surgeons in the present study have been early adopters of this technique, as evidenced by the gradual shift away from axillary cannulation in favor of innominate cannulation over the course of the study.

The CUSUM method, which was originally pioneered in the field of congenital cardiac surgery,²⁷ has since been applied to a variety of settings, such as minimally invasive coronary artery bypass grafting,²⁸ minimally invasive mitral valve repair,²⁹ the Ross procedure,^{30,31} and aortic valve repair.³² The study reported herein is the first to examine its use in thoracic aortic surgery with HCA. In addition, the present study is the largest published series reporting risk-adjusted CUSUM curves in the field of cardiothoracic surgery. Our findings highlight the

FIGURE 5. Summary of the study. Graphical abstract summarizing cohort characteristics (*left panel*), intraoperative details and perioperative outcomes (*central panel*), and risk-adjusted CUSUM analysis results (*right panel*). CUSUM, Cumulative sum.

importance of adjusting for baseline risk differences when comparing the performance of different surgeons. Indeed, 1 surgeon who was found to perform worse than expected on the unadjusted analysis, and another who was found to perform better than expected, both were found to perform as expected following risk adjustment.

The CUSUM analysis is a valuable method for monitoring individual surgeon performance. Unlike traditional retrospective audits—which only allow detection of outlying performance when the difference in outcomes has reached statistical significance—CUSUM analysis allows continuous monitoring and can quickly alert a surgeon to a deterioration in performance. As such, this analysis is particularly helpful for early-career surgeons attempting to monitor operative outcomes of patients undergoing aortic reconstruction with HCA. In addition, CUSUM analyses can be repeated as often as desired, providing an almost real-time monitoring of surgical performance.

The main limitation of this study is its retrospective, observational design. Despite a reasonable sample size, the incidence of many postoperative complications was low, making this study underpowered to detect subtle

differences in outcomes. Another limitation is the fact that not all surgeons performed equal number of cases. As such, a surgeon's "early" period may correspond—in terms of absolute volumes—to another surgeon's early and middle periods, for example. This study relied on internal standards—germane to the Canadian academic cardiac surgical environment—for risk adjustment and establishing acceptable performance. The use of external standards such as variables from the European System for Cardiac Operative Risk Evaluation II, national average values, or published results from expert centers in the field would have enhanced the generalizability of our findings. Finally, in the absence of established risk prediction scores for operations with HCA, the definition of what was considered an "acceptable" complication rate was by necessity somewhat arbitrary. Using more stringent boundary lines would have prolonged the learning curve. However, as the same criteria were applied consistently to the 8 participating surgeons, meaningful comparisons were still possible. These limitations notwithstanding, this large, multicenter study is the first to apply CUSUM methodology to the field of thoracic aortic surgery with HCA and represents a relevant addition to the current body of literature on surgical performance in cardiac surgery.

VIDEO 1. Summary of study design and main findings. Video available at: [https://www.jtcvs.org/article/S0022-5223\(18\)33263-X/fulltext](https://www.jtcvs.org/article/S0022-5223(18)33263-X/fulltext).

CONCLUSIONS

In conclusion, this study demonstrates that early-career surgeons can safely perform thoracic aortic operations with the use of HCA from the initiation of their practice (Figure 5). There is wide variability in individual surgeons' learning curves, but in a majority of cases, surgeons perform as expected throughout their experience. Overall operative mortality and incidence of adverse events compared favorably to published results from high-volume institutions with established expertise in thoracic aortic surgery. The CUSUM analysis

method is valuable for monitoring competence in aortic surgery and could prove useful in structuring training programs.

Webcast

You can watch a Webcast of this AATS meeting presentation by going to: <https://aats.blob.core.windows.net/media/18AO/26-br-1100-mazine-v2.mp4>.

Conflict of Interest Statement

Authors have nothing to disclose with regard to commercial support.

We acknowledge the contributions of Alana A. Harrington and Katie Losenno, who participated in data collection for this study. We also thank Dr Éric Dumont, who contributed cases to this analysis. Finally, we thank all members of the Canadian Thoracic Aortic Collaborative (Table E8), who provided feedback on this study.

References

- Barratt-Boyes B. Profound hypothermia—technical aspects. *Singapore Med J*. 1973;14:445-7.
- Gazoni LM, Speir AM, Kron IL, Fonner E, Crosby IK. Elective thoracic aortic aneurysm surgery: better outcomes from high-volume centers. *J Am Coll Surg*. 2010;210:855-9. 859-60.
- Miyata H, Motomura N, Ueda Y, Tsukihara H, Tabayashi K, Takamoto S. Toward quality improvement of thoracic aortic surgery: estimating volume-outcome effect from nationwide survey. *Eur J Cardiothorac Surg*. 2009;36:517-21.
- Hughes GC, Zhao Y, Rankin JS, Scarborough JE, O'Brien S, Bavaria JE, et al. Effects of institutional volumes on operative outcomes for aortic root replacement in North America. *J Thorac Cardiovasc Surg*. 2013;145:166-70.
- Rogers CA, Reeves BC, Caputo M, Ganesh JS, Bonser RS, Angelini GD. Control chart methods for monitoring cardiac surgical performance and their interpretation. *J Thorac Cardiovasc Surg*. 2004;128:811-9.
- Tibshirani R. Regression shrinkage and selection via the lasso. *J R Stat Soc Ser B*. 1996;58:267-88.
- Achneck HE, Rizzo JA, Tranquilli M, Elefteriades JA. Safety of thoracic aortic surgery in the present era. *Ann Thorac Surg*. 2007;84:1180-5; discussion 1185.
- Halkos ME, Kerendi F, Myung R, Kilgo P, Puskas JD, Chen EP. Selective antegrade cerebral perfusion via right axillary artery cannulation reduces morbidity and mortality after proximal aortic surgery. *J Thorac Cardiovasc Surg*. 2009;138:1081-9.
- Olsson C, Eriksson N, Stahle E, Thelin S. Surgical and long-term mortality in 2634 consecutive patients operated on the proximal thoracic aorta. *Eur J Cardiothorac Surg*. 2007;31:963-9; discussion 969.
- Tian DH, Wan B, Bannon PG, Misfeld M, LeMaire SA, Kazui T, et al. A meta-analysis of deep hypothermic circulatory arrest versus moderate hypothermic circulatory arrest with selective antegrade cerebral perfusion. *Ann Cardiothorac Surg*. 2013;2:148-58.
- Preventza O, Garcia A, Tuluca A, Henry M, Cooley DA, Simpson K, et al. Innominate artery cannulation for proximal aortic surgery: outcomes and neurological events in 263 patients. *Eur J Cardiothorac Surg*. 2015;48:937-42; discussion 942.
- Ziganshin BA, Rajbanshi BG, Tranquilli M, Fang H, Rizzo JA, Elefteriades JA. Straight deep hypothermic circulatory arrest for cerebral protection during aortic arch surgery: safe and effective. *J Thorac Cardiovasc Surg*. 2014;148:888-98; discussion 898-900.
- Murzi M, Miceli A, Di Stefano G, Cerillo AG, Kallushi E, Farneti P, et al. Enhancing quality control and performance monitoring in thoracic aortic surgery: a 10-year single institutional experience. *Eur J Cardiothorac Surg*. 2015;47:608-15.
- Gutsche JT, Ghadimi K, Patel PA, Robinson AR III, Lane BJ, Szeto WY, et al. New frontiers in aortic therapy: focus on deep hypothermic circulatory arrest. *J Cardiothorac Vasc Anesth*. 2014;28:1159-63.
- Leshnower BG, Myung RJ, Kilgo PD, Vassiliades TA, Vega JD, Thourani VH, et al. Moderate hypothermia and unilateral selective antegrade cerebral perfusion: a contemporary cerebral protection strategy for aortic arch surgery. *Ann Thorac Surg*. 2010;90:547-54.
- Leshnower BG, Myung RJ, Thourani VH, Halkos ME, Kilgo PD, Puskas JD, et al. Hemiarch replacement at 28 degrees C: an analysis of mild and moderate hypothermia in 500 patients. *Ann Thorac Surg*. 2012;93:1910-5; discussion 1915-6.
- Peterson MD, Mazine A, El-Hamamsy I, Manlihot C, Ouzounian M, MacArthur RG, et al. Knowledge, attitudes, and practice preferences of Canadian cardiac surgeons toward the management of acute type A aortic dissection. *J Thorac Cardiovasc Surg*. 2015;150:824-31.e821-5.
- Ehrlich MP, Hagl C, McCullough JN, Zhang N, Shiang H, Bodian C, et al. Retrograde cerebral perfusion provides negligible flow through brain capillaries in the pig. *J Thorac Cardiovasc Surg*. 2001;122:331-8.
- Appoo JJ, Bozinovski J, Chu MW, El-Hamamsy I, Forbes TL, Moon M, et al. Canadian Cardiovascular Society/Canadian Society of Cardiac Surgeons/Canadian Society for Vascular Surgery Joint Position Statement on Open and Endovascular Surgery for Thoracic Aortic Disease. *Can J Cardiol*. 2016;32:703-13.
- El-Hamamsy I, Ouzounian M, Demers P, McClure S, Hassan A, Dagenais F, et al. State-of-the-art surgical management of acute type A aortic dissection. *Can J Cardiol*. 2016;32:100-9.
- Gulbins H, Pritisanac A, Ennker J. Axillary versus femoral cannulation for aortic surgery: enough evidence for a general recommendation? *Ann Thorac Surg*. 2007;83:1219-24.
- Moizumi Y, Motoyoshi N, Sakuma K, Yoshida S. Axillary artery cannulation improves operative results for acute type A aortic dissection. *Ann Thorac Surg*. 2005;80:77-83.
- Reuthebuch O, Schurr U, Hellermann J, Pretre R, Kunzli A, Lachat M, et al. Advantages of subclavian artery perfusion for repair of acute type A dissection. *Eur J Cardiothorac Surg*. 2004;26:592-8.
- Svensson LG, Blackstone EH, Rajeswaran J, Sabik JF III, Lytle BW, Gonzalez-Stawinski G, et al. Does the arterial cannulation site for circulatory arrest influence stroke risk? *Ann Thorac Surg*. 2004;78:1274-84; discussion 1274-84.
- Chu MW, Losenno KL, Gelinas JJ, Garg V, Dickson J, Harrington A, et al. Innominate and axillary cannulation in aortic arch surgery provide similar neuroprotection. *Can J Cardiol*. 2016;32:117-23.
- Garg V, Tsigotis DN, Dickson J, Dalamagas C, Latter DA, Verma S, et al. Direct innominate artery cannulation for selective antegrade cerebral perfusion during deep hypothermic circulatory arrest in aortic surgery. *J Thorac Cardiovasc Surg*. 2014;148:2920-4.
- de Leval MR, Carthy J, Wright DJ, Farewell VT, Reason JT. Human factors and cardiac surgery: a multicenter study. *J Thorac Cardiovasc Surg*. 2000;119:661-72.
- Holzhey DM, Jacobs S, Walther T, Mochalski M, Mohr FW, Falk V. Cumulative sum failure analysis for eight surgeons performing minimally invasive direct coronary artery bypass. *J Thorac Cardiovasc Surg*. 2007;134:663-9.
- Holzhey DM, Seeburger J, Misfeld M, Borger MA, Mohr FW. Learning minimally invasive mitral valve surgery: a cumulative sum sequential probability analysis of 3895 operations from a single high-volume center. *Circulation*. 2013;128:483-91.
- Stelzer P, Itagaki S, Varghese R, Chikwe J. Operative mortality and morbidity after the Ross procedure: a 26-year learning curve. *J Heart Valve Dis*. 2013;22:767-75.
- Bouhout I, Ghoneim A, Poirier N, Cartier R, Demers P, Perrault LP, et al. Impact of the learning curve on early outcomes following the Ross procedure. *Can J Cardiol*. 2017;33:493-500.
- Malas T, Sackowski R, Sohmer B, Ruel M, Mesana T, de Kerchove L, et al. Is Aortic valve repair reproducible? Analysis of the learning curve for aortic valve repair. *Can J Cardiol*. 2015;31:1497.e1415-22.

Key Words: performance curve, circulatory arrest, cumulative sum analysis

TABLE E1. Multivariable analysis of factors associated with the composite safety endpoint

Risk factors	Odds ratio (95% CI)	P value
Age (per 10 y)	1.40 (1.24-1.58)	<.001
Female sex	0.99 (0.72-1.36)	.945
Body mass index	0.92 (0.77-1.09)	.342
History of CVD or PVD	1.58 (1.10-2.28)	.013
History of smoking or COPD	1.54 (1.16-2.05)	.003
Emergent or salvage operation	2.47 (1.47-4.15)	<.001
Aortic dissection or rupture	1.72 (1.09-2.72)	.020
Coronary artery disease	1.48 (1.04-2.11)	.030
Concomitant procedure	1.36 (0.99-1.86)	.056
Total arch replacement	1.40 (0.98-2.01)	.068

CI, Confidence interval; *CVD*, cerebrovascular disease; *PVD*, peripheral vascular disease; *COPD*, chronic obstructive pulmonary disease.

TABLE E2. Baseline patient characteristics in each period

	First third (n = 339)	Second third (n = 344)	Third third (n = 342)	P value*
Age, y, mean $\pm$ SD	62 $\pm$ 14	63 $\pm$ 13	62 $\pm$ 13	.503
Female sex	101 (30%)	96 (28%)	104 (30%)	.750
Body mass index, kg/m ² , mean $\pm$ SD	28 $\pm$ 5	28 $\pm$ 5	29 $\pm$ 6	.005
NYHA class III or IV	87 (26%)	83 (24%)	74 (22%)	.458
LVEF <40%	17 (5%)	17 (5%)	26 (8%)	.269
Previous cardiac surgery	44 (13%)	53 (15%)	54 (16%)	.534
Risk factors, (%)				
Smoking	148 (44)	133 (39)	127 (37)	.190
Hypertension	231 (68)	245 (71)	234 (68)	.628
Diabetes mellitus	32 (9)	44 (13)	38 (11)	.389
Dyslipidemia	158 (47)	167 (49)	176 (51)	.467
Comorbidities, (%)				
Coronary artery disease	74 (22)	70 (20)	78 (23)	.735
Previous myocardial infarction	25 (7)	22 (6)	25 (7)	.853
Congestive heart failure	31 (10)	36 (11)	25 (8)	.339
Atrial fibrillation	49 (14)	45 (13)	42 (13)	.745
Peripheral vascular disease	32 (9)	34 (10)	34 (10)	.973
History of stroke	20 (6)	15 (4)	17 (5)	.649
History of TIA	18 (5)	16 (5)	13 (4)	.634
Any cerebrovascular disease	39 (12)	34 (10)	29 (8)	.423
History of chronic renal disease	38 (11)	32 (9)	33 (10)	.676
COPD	52 (15)	45 (13)	30 (9)	.028
Connective tissue disorder†	18 (5)	12 (3)	15 (4)	.777
Thoracic aortic pathology, (%)‡				
Aortic aneurysm	290 (86)	294 (85)	316 (92)	.005
Aortic dissection	86 (25)	84 (24)	58 (17)	.013
Aortic rupture	15 (4)	9 (3)	8 (2)	.251
Maximum aortic diameter, mm, mean $\pm$ SD	56 $\pm$ 11	54 $\pm$ 10	54 $\pm$ 10	.002
Aortic valve pathology, (%)‡				
Aortic stenosis	89 (26)	98 (28)	101 (30)	.627
Aortic insufficiency§	50 (15)	54 (16)	96 (28)	<.001
Morphology, (%)				.752
Tricuspid	220 (65)	234 (69)	226 (67)	
Bicuspid	115 (34)	98 (29)	108 (32)	
Unicuspid	2 (1)	6 (2)	4 (1)	
Presentation status, (%)				.044
Elective	237 (70)	262 (76)	274 (80)	
Urgent	31 (9)	21 (6)	31 (9)	
Emergent	64 (19)	58 (17)	33 (10)	
Salvage	7 (2)	3 (1)	4 (1)	

SD, Standard deviation; NYHA, New York Heart Association; LVEF, left ventricular ejection fraction; TIA, transient ischemic attack; COPD, chronic obstructive pulmonary disease. *Continuous variables were compared using analysis of variance. Categorical variables were compared using Pearson χ^2 test or Fisher exact test, as appropriate.

†Genetically confirmed. ‡Not mutually exclusive. §Greater than mild.

TABLE E3. Baseline patient characteristics for each surgeon

	Surgeon A (n = 155)	Surgeon B (n = 90)	Surgeon C (n = 174)	Surgeon D (n = 94)	Surgeon E (n = 70)	Surgeon F (n = 239)	Surgeon G (n = 59)	Surgeon H (n = 144)	P value
Age, y, mean $\pm$ SD	63 $\pm$ 13	63 $\pm$ 13	64 $\pm$ 14	56 $\pm$ 16	65 $\pm$ 14	61 $\pm$ 12	63 $\pm$ 14	64 $\pm$ 11	<.001
Female sex	46 (30%)	26 (29%)	58 (33%)	28 (30%)	27 (39%)	62 (26%)	22 (37%)	32 (22%)	.150
Body mass index, kg/m ² , mean $\pm$ SD	27 $\pm$ 5	28 $\pm$ 5	28 $\pm$ 5	29 $\pm$ 6	29 $\pm$ 7	29 $\pm$ 5	30 $\pm$ 6	28 $\pm$ 5	.026
NYHA class III or IV	42 (27%)	19 (21%)	40 (23%)	16 (17%)	0 (0%)	73 (31%)	9 (15%)	45 (31%)	.053
LVEF <40%	6 (4%)	6 (7%)	15 (9%)	0 (0%)	1 (1%)	20 (8%)	2 (3%)	10 (7%)	.383
Previous cardiac surgery	34 (22%)	12 (13%)	20 (11%)	12 (13%)	17 (24%)	29 (12%)	9 (15%)	18 (13%)	.039
Risk factors, (%)									
Smoking	33 (21)	19 (21)	81 (47)	31 (33)	31 (44)	110 (46)	29 (49)	74 (51)	<.001
Hypertension	95 (61)	57 (63)	123 (71)	53 (56)	52 (74)	186 (78)	41 (69)	103 (72)	.002
Diabetes mellitus	13 (8)	11 (12)	17 (10)	8 (9)	9 (13)	28 (12)	9 (15)	19 (13)	.763
Dyslipidemia	103 (66)	58 (64)	79 (45)	43 (46)	22 (32)	100 (42)	28 (47)	68 (47)	<.001
Comorbidities, (%)									
Coronary artery disease	46 (30)	18 (20)	27 (16)	19 (20)	19 (27)	45 (19)	13 (22)	35 (24)	.079
Previous myocardial infarction	17 (11)	3 (3)	7 (4)	4 (4)	4 (6)	19 (8)	0 (0)	18 (13)	.052
Congestive heart failure	5 (3)	4 (4)	15 (9)	3 (3)	0 (0)	20 (8)	16 (27)	29 (20)	<.001
Atrial fibrillation	25 (16)	9 (10)	27 (16)	9 (10)	8 (11)	25 (10)	9 (19)	24 (17)	.31
Peripheral vascular disease	23 (15)	12 (13)	19 (11)	7 (7)	8 (11)	10 (4)	5 (8)	16 (11)	.043
History of stroke	15 (10)	6 (7)	11 (6)	3 (3)	0 (0)	9 (4)	0 (0)	8 (6)	.419
History of TIA	6 (4)	2 (2)	13 (7)	4 (4)	0 (0)	4 (2)	6 (10)	12 (8)	.044
Any cerebrovascular disease	21 (14)	8 (9)	24 (14)	7 (7)	4 (6)	13 (5)	5 (8)	20 (14)	.042
History of chronic renal disease	24 (15)	18 (20)	5 (3)	9 (10)	6 (9)	4 (2)	2 (3)	35 (24)	<.001
COPD	24 (15)	8 (9)	23 (13)	9 (10)	5 (7)	18 (8)	11 (19)	29 (20)	.007
Connective tissue disorder*	2 (1)	0 (0)	10 (6)	6 (6)	2 (3)	4 (2)	8 (14)	13 (9)	.005
Thoracic aortic pathology, (%)†									
Aortic aneurysm	136 (88)	83 (92)	139 (80)	82 (87)	65 (93)	208 (87)	51 (86)	136 (94)	.010
Aortic dissection	41 (26)	23 (26)	29 (17)	21 (22)	24 (34)	34 (14)	19 (32)	37 (26)	.001
Aortic rupture	5 (3)	3 (3)	8 (5)	0 (0)	2 (3)	7 (3)	1 (2)	6 (4)	.974
Maximum aortic diameter, mm, mean $\pm$ SD	57 $\pm$ 13	55 $\pm$ 10	55 $\pm$ 10	52 $\pm$ 9	57 $\pm$ 11	55 $\pm$ 8	56 $\pm$ 9	51 $\pm$ 10	<.001
Aortic valve pathology, (%)‡									
Aortic stenosis	25 (16)	21 (23)	47 (27)	31 (33)	8 (11)	83 (35)	22 (37)	51 (35)	<.001
Aortic insufficiency‡	101 (65)	58 (64)	23 (13)	0 (0)	0 (0)	0 (0)	17 (29)	1 (1)	<.001
Morphology									<.001
Tricuspid	116 (75)	64 (71)	111 (64)	59 (63)	52 (81)	146 (61)	33 (61)	99 (69)	
Bicuspid	38 (25)	26 (29)	54 (31)	35 (37)	12 (19)	90 (38)	21 (39)	45 (31)	
Unicuspid	0 (0)	0 (0)	9 (5)	0 (0)	0 (0)	3 (1)	0 (0)	0 (0)	
Presentation status, (%)									
Elective	128 (83)	69 (77)	125 (72)	69 (73)	43 (61)	212 (89)	36 (61)	91 (63)	<.001
Urgent	6 (4)	7 (8)	22 (13)	2 (2)	8 (11)	8 (3)	8 (14)	22 (15)	
Emergent	20 (13)	12 (13)	21 (12)	23 (24)	19 (27)	18 (8)	15 (25)	27 (19)	
Salvage	1 (1)	2 (2)	6 (3)	0 (0)	0 (0)	1 (0)	0 (0)	4 (3)	

SD, Standard deviation; NYHA, New York Heart Association; LVEF, left ventricular ejection fraction; TIA, transient ischemic attack; COPD, chronic obstructive pulmonary disease. *Genetically confirmed. †Not mutually exclusive. ‡Greater than mild.

TABLE E4. Operative details in each period

	First third (n = 339)	Second third (n = 344)	Third third (n = 342)	P value*
Thoracic aortic procedure, (%)†				
Hemiarch replacement	272 (80)	269 (78)	277 (81)	.638
Total arch replacement	66 (19)	72 (21)	63 (18)	.710
Elephant trunk	43 (13)	40 (12)	51 (15)	.437
Aortic valve and/or root procedure, (%)†				
Aortic valve replacement	56 (17)	49 (14)	73 (21)	.045
Biological	34 (10)	38 (11)	57 (17)	
Mechanical	22 (6)	11 (3)	16 (5)	
Bentall procedure	115 (34)	122 (35)	96 (28)	.089
Biological	61 (18)	72 (21)	66 (19)	
Mechanical	54 (16)	50 (15)	30 (9)	
Aortic valve repair	67 (20)	71 (21)	61 (18)	.643
Valve-sparing root replacement	27 (8)	42 (12)	55 (16)	.005
Ross procedure	7 (2)	10 (3)	16 (5)	.159
Sinus root repair	27 (8)	19 (6)	34 (10)	.096
Concomitant procedures, (%)†				
CABG	61 (18)	71 (21)	71 (21)	.597
Mitral valve repair	7 (2)	7 (2)	11 (3)	.533
Mitral valve replacement	6 (2)	2 (1)	5 (1)	.329
ASD/VSD repair	7 (2)	1 (0)	4 (1)	.075
Other concomitant procedures	26 (8)	34 (10)	29 (8)	.591
Arterial cannulation, (%)†				
Femoral	28 (8)	19 (6)	17 (5)	.171
Axillary	241 (72)	180 (52)	129 (38)	<.001
Innominate	48 (14)	108 (31)	155 (46)	<.001
Carotid	0	3 (1)	4 (1)	.156
Distal arch	48 (14)	47 (14)	62 (18)	.206
Elephant trunk graft	12 (4)	59 (17)	54 (16)	<.001
Perfusion details				
CPB time, min, median [IQR]	166 [129, 219]	168 [130, 225]	165 [121, 214]	.183
Aortic crossclamp time, min, median [IQR]	110 [78, 155]	123 [80, 166]	116 [85, 168]	.150
HCA duration, min, median [IQR]	20 [14, 31]	21 [14, 31]	20 [11, 26]	.029
Long HCA duration (>40 min)	54 (16%)	49 (14%)	42 (12%)	.393
HCA lowest temperature, °C, median [IQR]	20 [18, 24]	25 [22, 26]	25 [24, 27]	<.001
Cerebral perfusion, (%)				.008
None	38 (11)	25 (7)	35 (10)	
Antegrade	291 (86)	317 (92)	301 (88)	
Retrograde	10 (3)	2 (1)	6 (2)	

CABG, Coronary artery bypass grafting; ASD, atrial septal defect; VSD, ventricular septal defect; CPB, cardiopulmonary bypass; IQR, interquartile range; HCA, hypothermic circulatory arrest. *Continuous variables were compared using analysis of variance. Categorical variables were compared using Pearson's χ^2 test or Fisher exact test, as appropriate. Boldface denotes statistically significant *P* values. †Not mutually exclusive.

TABLE E5. Operative details for each surgeon

	Surgeon A (n = 155)	Surgeon B (n = 90)	Surgeon C (n = 174)	Surgeon D (n = 94)	Surgeon E (n = 70)	Surgeon F (n = 239)	Surgeon G (n = 59)	Surgeon H (n = 144)	P value
Thoracic aortic procedure, (%)*									
Hemiarch replacement	110 (71)	84 (93)	115 (66)	90 (96)	59 (84)	199 (83)	49 (83)	112 (78)	<.001
Total arch replacement	43 (28)	6 (7)	59 (34)	3 (3)	12 (17)	38 (16)	11 (19)	29 (20)	<.001
Elephant trunk	30 (19)	2 (2)	42 (24)	1 (1)	4 (6)	32 (13)	10 (17)	13 (9)	<.001
Aortic valve and/or root procedure, (%)*									
Aortic valve replacement	34 (22)	31 (34)	9 (5)	10 (11)	7 (10)	57 (24)	11 (19)	19 (13)	<.001
Biological	27 (17)	20 (22)	8 (5)	8 (9)	5 (7)	40 (17)	8 (14)	13 (9)	
Mechanical	7 (5)	11 (12)	1 (1)	2 (2)	2 (3)	17 (7)	3 (5)	6 (4)	
Bentall procedure	51 (33)	17 (19)	72 (41)	19 (20)	7 (10)	75 (31)	16 (27)	76 (53)	<.001
Biological	22 (14)	7 (8)	50 (29)	17 (18)	3 (4)	40 (17)	9 (15)	51 (35)	
Mechanical	29 (19)	10 (11)	22 (13)	2 (2)	4 (6)	35 (15)	7 (12)	25 (17)	
Aortic valve repair	34 (22)	29 (32)	30 (17)	21 (22)	38 (54)	20 (8)	5 (8)	22 (15)	<.001
Valve-sparing root replacement	15 (10)	0 (0)	41 (24)	14 (15)	13 (19)	27 (11)	4 (7)	10 (7)	<.001
Ross procedure	0 (0)	0 (0)	6 (3)	21 (22)	0 (0)	6 (3)	0 (0)	0 (0)	<.001
Sinus root repair	11 (7)	11 (12)	25 (14)	1 (1)	1 (1)	11 (5)	10 (17)	10 (7)	<.001
Concomitant procedures, (%)*									
CABG	50 (32)	18 (20)	26 (15)	9 (10)	8 (11)	44 (18)	9 (15)	39 (27)	<.001
Mitral valve repair	7 (5)	4 (4)	1 (1)	1 (1)	0 (0)	4 (2)	0 (0)	8 (6)	.216
Mitral valve replacement	4 (3)	0 (0)	4 (2)	2 (2)	2 (3)	1 (0)	0 (0)	0 (0)	.880
ASD/VSD repair	1 (1)	1 (1)	2 (1)	1 (1)	2 (3)	2 (1)	1 (2)	2 (1)	.940
Other concomitant procedures	32 (21)	13 (14)	13 (7)	1 (1)	6 (9)	9 (4)	2 (3)	13 (9)	<.01
Arterial cannulation, (%)*									
Femoral	13 (8)	7 (8)	12 (7)	2 (2)	8 (11)	16 (7)	4 (7)	2 (1)	.129
Axillary	101 (66)	57 (63)	121 (70)	17 (18)	61 (87)	87 (36)	9 (16)	97 (67)	<.001
Innominate	18 (12)	13 (14)	49 (28)	13 (14)	0 (0)	138 (58)	37 (66)	43 (30)	<.001
Carotid	2 (1)	0 (0)	2 (1)	0 (0)	0 (0)	2 (1)	1 (2)	0 (0)	1.000
Distal arch	56 (36)	26 (29)	1 (1)	62 (66)	1 (1)	1 (0)	7 (13)	3 (2)	<.001
Elephant trunk graft	0 (0)	0 (0)	112 (64)	13 (14)	0 (0)	0 (0)	0 (0)	0 (0)	<.001
Perfusion details									
CPB time, min,	127	132	231	171	170	155	160	180	<.001
median [IQR]	[101, 167]	[108, 168]	[191, 277]	[123, 211]	[125, 235]	[130, 200]	[134, 192]	[140, 242]	
Aortic crossclamp time,	83	91	167	131	102	121	111	141	<.001
min, median [IQR]	[59, 105]	[66, 112]	[124, 216]	[87, 176]	[74, 151]	[86, 154]	[70, 143]	[102, 187]	
HCA duration, min,	9 [6, 17]	12 [10, 15]	29 [23, 42]	13 [10, 17]	22 [16, 32]	20 [18, 26]	17 [12, 22]	20 [15, 42]	<.001
median [IQR]									
Long HCA duration (>40 min)	9 (6%)	2 (2%)	45 (26%)	5 (5%)	2 (3%)	37 (15%)	8 (14%)	37 (26%)	<.001
HCA lowest temperature, °C, median [IQR]	20 [17, 24]	23 [19, 25]	25 [25, 26]	25 [20, 26]	22 [19, 34]	24 [20, 26]	24 [24, 26]	25 [18, 28]	<.001
Cerebral perfusion, (%)									<.001
None	12 (8)	10 (11)	0 (0)	68 (72)	2 (3)	1 (0)	2 (3)	3 (2)	
Antegrade	134 (86)	79 (88)	174 (100)	26 (28)	68 (97)	238 (100)	50 (85)	140 (97)	
Retrograde	9 (6)	1 (1)	0 (0)	0 (0)	0 (0)	0 (0)	7 (12)	1 (1)	

CABG, Coronary artery bypass grafting; ASD, atrial septal defect; VSD, ventricular septal defect; CPB, cardiopulmonary bypass; IQR, interquartile range; HCA, hypothermic circulatory arrest. *Not mutually exclusive.

TABLE E6. Perioperative outcomes in each period

	First third (n = 339)	Second third (n = 344)	Third third (n = 342)	P value*
Primary safety outcome, (%)				
≥1 major complications†	87 (26)	78 (23)	56 (16)	.010
In-hospital or 30-d mortality	22 (6)	16 (5)	16 (5)	.495
Stroke	14 (4)	22 (6)	8 (2)	.035
Reoperation for bleeding	36 (11)	27 (8)	24 (7)	.222
Dialysis-dependent renal failure	12 (4)	17 (5)	7 (2)	.122
>40 h of mechanical ventilation	48 (14)	39 (11)	20 (6)	.001
Sternal dehiscence/mediastinitis	6 (2)	2 (1)	2 (1)	.196
Other adverse events, (%)				
Myocardial infarction	3 (1)	3 (1)	9 (3)	.114
Postoperative IABP requirement	2 (1)	0	0	.109
Postoperative atrial fibrillation	137 (41)	133 (39)	105 (31)	.017
Cardiac arrest/malignant arrhythmia	13 (4)	5 (1)	12 (4)	.108
Spinal cord injury	4 (1)	4 (1)	1 (0)	.379
Transient ischemic attack	5 (2)	11 (3)	2 (1)	.034
Delirium	66 (19)	83 (24)	49 (14)	.005
Septic shock	7 (2)	4 (1)	3 (1)	.392
Blood product transfusion, (%)				
Packed red blood cells	150 (44)	116 (34)	86 (25)	<.001
Fresh-frozen plasma	196 (58)	125 (36)	120 (35)	<.001
Platelets	190 (56)	147 (43)	121 (35)	<.001
Factor VII	29 (9)	19 (6)	14 (4)	.048
ICU length of stay, d, median [IQR]	2 [1, 5]	2 [1, 4]	2 [1, 3]	.002
ICU length of stay ≥4 d	112 (33%)	87 (25%)	73 (21%)	.002
Hospital length of stay, d, median [IQR]	8 [6, 13]	7 [5, 11]	7 [5, 10]	.006

IABP, Intra-aortic balloon pump; ICU, intensive care unit; IQR, interquartile range. *Continuous variables were compared using analysis of variance. Categorical variables were compared using Pearson χ^2 test or Fisher exact test, as appropriate. Boldface denotes statistically significant P values. †Major complications defined as the occurrence of at least 1 of the following: death, stroke, bleeding requiring re-exploration, acute renal failure requiring dialysis, long duration of postoperative mechanical ventilation (>40 hours), and sternal dehiscence/mediastinitis.

TABLE E7. Perioperative outcomes for each surgeon

	Surgeon A (n = 155)	Surgeon B (n = 90)	Surgeon C (n = 174)	Surgeon D (n = 94)	Surgeon E (n = 70)	Surgeon F (n = 239)	Surgeon G (n = 59)	Surgeon H (n = 144)	P value
Primary safety endpoint, (%)									
≥1 major complications*	32 (21)	19 (21)	33 (19)	24 (26)	17 (24)	36 (15)	10 (17)	50 (35)	.002
In-hospital or 30-d mortality	8 (5)	6 (7)	6 (3)	2 (2)	5 (7)	7 (3)	4 (7)	16 (11)	.037
Stroke	8 (5)	4 (4)	4 (2)	3 (3)	3 (4)	10 (4)	3 (5)	9 (6)	.831
Reoperation for bleeding	12 (8)	13 (14)	11 (6)	5 (5)	7 (10)	21 (9)	1 (2)	17 (12)	.140
Dialysis-dependent renal failure	3 (2)	1 (1)	3 (2)	10 (11)	6 (9)	5 (2)	3 (5)	5 (3)	.004
>40 h of mechanical ventilation	15 (10)	3 (3)	23 (13)	16 (17)	13 (19)	2 (1)	7 (12)	28 (19)	<.001
Sternal dehiscence/mediastinitis	0 (0)	0 (0)	2 (1)	1 (1)	1 (1)	1 (0)	0 (0)	5 (3)	.647
Other adverse events, (%)									
Myocardial infarction	5 (3)	2 (2)	0 (0)	1 (1)	0 (0)	1 (0)	2 (3)	4 (3)	.710
Postoperative IABP requirement	1 (1)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	1 (2)	0 (0)	.999
Postoperative atrial fibrillation	70 (45)	45 (50)	39 (22)	37 (39)	36 (55)	77 (32)	26 (44)	45 (31)	<.001
Cardiac arrest/malignant arrhythmia	4 (3)	1 (1)	3 (2)	2 (2)	4 (6)	7 (3)	1 (2)	8 (6)	.407
Spinal cord injury	2 (1)	3 (3)	3 (2)	0 (0)	0 (0)	1 (0)	0 (0)	0 (0)	.826
Transient ischemic attack	9 (6)	3 (3)	2 (1)	3 (3)	0 (0)	0 (0)	1 (2)	0 (0)	.488
Delirium	47 (30)	18 (20)	11 (6)	25 (27)	8 (12)	49 (21)	11 (19)	29 (20)	<.001
Septic shock	1 (1)	0 (0)	0 (0)	3 (3)	0 (0)	2 (1)	2 (3)	6 (4)	.395
Blood product transfusion, (%)									
Packed red blood cells	30 (19)	14 (16)	76 (44)	36 (38)	37 (53)	75 (31)	35 (59)	49 (34)	<.001
Fresh-frozen plasma	95 (61)	52 (58)	64 (37)	27 (29)	29 (41)	79 (33)	29 (49)	66 (46)	<.001
Platelets	113 (73)	61 (68)	57 (33)	33 (35)	33 (47)	79 (33)	39 (66)	43 (30)	<.001
Factor VII	1 (1)	1 (1)	18 (10)	4 (4)	4 (6)	22 (9)	11 (19)	1 (1)	<.001
ICU length of stay, d, median [IQR]	3 [1, 5]	1 [1, 3]	1 [1, 3]	2 [2, 5]	2 [1, 5]	1 [1, 3]	2 [1, 4]	2 [1, 4]	<.001
ICU length of stay ≥4 d	47 (30%)	13 (14%)	40 (23%)	31 (33%)	22 (31%)	58 (24%)	13 (22%)	48 (33%)	.25
Hospital length of stay, d, median [IQR]	8 [6, 11]	7 [5, 10]	8 [6, 13]	7 [5, 10]	10 [6, 15]	7 [5, 10]	8 [6, 13]	8 [5, 12]	.011

IABP, Intra-aortic balloon pump; ICU, intensive care unit; IQR, interquartile range. *Major complications defined as the occurrence of at least 1 of the following: death, stroke, bleeding requiring reintervention, acute renal failure requiring dialysis, long duration of postoperative mechanical ventilation (>40 hours), and sternal dehiscence/mediastinitis.

TABLE E8. List of members of the Canadian Thoracic Aortic Collaborative

Name	Institution	City
Chu, Michael W.A.	Western University	London, ON
Adams, Corey	Memorial University	St. John's, NL
Atoui, Rony	Northern Ontario School of Medicine (NOSM)	Sudbury, ON
Appoo, Jehangir	University of Calgary	Calgary, AB
Bittira, Bindu	Sudbury Regional Hospital-Memorial Site	Sudbury, ON
Boodhwani, Munir	University of Ottawa	Ottawa, ON
Bouhout, Ismail	University of Montreal	Montreal, QC
Bozinovski, John	Royal Jubilee Hospital	Victoria, BC
Cartier, Raymond	University of Montreal	Montreal, QC
Chung, Jennifer	University of Toronto	Toronto, ON
Cutrara, Charles	U of Toronto (Trillium)	Mississauga, ON
Dagenais, Francois	Laval University	Quebec City, QC
Demers, Phillippe	University of Montreal	Montreal, QC
Dumont, Eric	Laval University	Quebec City, QC
El-Hamamsy, Ismail	University of Montreal	Montreal, QC
Fedak, Paul	University of Calgary	Calgary, AB
Ghoneim, Aly	McGill University	Montreal, QC
Guo, Ray	Western University	London, ON
Hassan, Ansar	Saint John Regional Hospital	St. John, NB
Herman, Christine	Dalhousie University	Halifax, NS
Kumar, Kanwal	University of Manitoba	Winnipeg, MB
Lachapelle, Kevin	McGill University	Montreal, QC
Lodewyck, Carly	University of Manitoba	Winnipeg, MB
MacArthur, Roderick	University of Alberta	Edmonton, AB
Mazine, Amine	University of Toronto	Toronto, ON
McClure, Scott	University of Calgary	Calgary, AB
Moon, Michael	University of Alberta	Edmonton, AB
Ouzounian, Maral	University of Toronto	Toronto, ON
Payne, Darrin	Queens University	Kingston, ON
Peterson, Mark	University of Toronto	Toronto, ON
Poirier, Nancy	University of Montreal	Montreal, QC
Poostizadeh, Ahmad	University of British Columbia	Kelowna, BC
Pozeg, Zlatko	Saint John Regional Hospital	St. John, NB
Salasidis, Gary	St. Mary's Hospital	Kitchener-Waterloo, ON
Stevens, Louis-Mathieu	University of Montreal	Montreal, QC
Tarola, Chris	Western University	London, ON
Tsang, John	University of Saskatchewan	Regina, SK
Valdis, Matt	Western University	London, ON
Whitlock, Richard	McMaster University	Hamilton, ON
Wong, Daniel	University of British Columbia	Vancouver, BC
Wood, Jeremy	Dalhousie University	Halifax, NS
Yamashita, Michael	University of Manitoba	Winnipeg, MB