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Cerebral Blood Flow Autoregulation Is Preserved After Hypothermic Circulatory Arrest

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Abstract

Background—Patients undergoing aortic surgery with hypothermic circulatory arrest (HCA) may require prolonged rewarming, a maneuver associated with impaired cerebral blood flow (CBF) autoregulation. The purpose of this study was to determine the effects of HCA on CBF autoregulation with validated method based on near-infrared spectroscopy.

Methods—Regional cerebral oxygen saturation (rScO₂) was monitored in 25 patients undergoing aortic reconstructive surgery. HCA was used in 13 patients. Autoregulation was measured continuously during surgery by calculating the linear correlation coefficient between low-frequency changes in rScO₂ and mean arterial pressure (MAP), generating the variable cerebral oximetry index (COx). When CBF autoregulation is functional, COx is near zero, as CBF and MAP are not correlated, but it approaches 1 when autoregulation is impaired (i.e., CBF is pressure passive). Based on prior studies, impaired autoregulation was defined as COx > 0.3.

Results—COx did not differ between HCA and non-HCA groups before cardiopulmonary bypass or during the cooling phase of surgery, although the lower limit of autoregulation tended to be lower in patients before HCA ($p=0.053$). During patient rewarming, COx was lower in the HCA group ($p=0.045$) and abnormal COx was less frequent (31% vs 75%, $p=0.047$) compared with the non-HCA group.

Conclusions—During aortic reconstructive surgery, CBF autoregulation is preserved during the cooling phase of surgery in patients undergoing HCA. Perfusion maneuvers associated with HCA

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may be protective against impaired autoregulation during rewarming compared with the non-HCA group.

Keywords

Aorta operations; cerebral autoregulation

Introduction

Cerebral blood flow (CBF) autoregulation remains functional during mild hypothermic cardiopulmonary bypass (CPB) when alpha-stat pH management is used thus ensuring a steady supply of oxygenated blood to the brain over a wide range of blood pressures (1). However, impairment of autoregulation is reported in up to 20% of adult patients during CPB, particularly during rewarming (2, 3). In the absence of functional autoregulation, CBF is pressure passive, which may cause cerebral ischemia with low blood pressure or cerebral hyperemia with high blood pressure, predisposing patients to cerebral ischemia or edema and delirium, respectively (4). We have previously reported that impaired autoregulation during CPB is associated with postoperative stroke (2, 3).

Surgical repair of aortic aneurysms and aortic dissections often require deep hypothermia (18°C to 20°C) with circulatory arrest (HCA) and/or antegrade selective cerebral perfusion (SACP). Several studies in neonates, infants, and adults have suggested that CBF autoregulation is impaired by HCA, with the magnitude of impairment attenuated by SACP (5, 6). In those studies, only several discrete measurements of CBF were obtained in each subject while blood pressure was manipulated. Such autoregulation testing methods allow one to determine only the presence or absence of functional autoregulation at set testing intervals and may fail to account for the dynamic effects of other perioperative perturbations, including anemia, on autoregulation (7–9).

CBF autoregulation can be monitored *continuously* in surgical and critically ill patients by measuring the moving linear regression correlation coefficient between low-frequency changes in near-infrared spectroscopy (NIRS)-measured regional cerebral oxygen saturation (rScO₂) and mean arterial blood pressure (MAP) (10–12). In this instance, rScO₂ serves as a surrogate for CBF that compares favorably with transcranial Doppler measurement of CBF velocity. Continuous monitoring of CBF autoregulation might provide higher resolution than intermittent testing provides for determining the effects of HCA on cerebral homeostatic mechanisms. Further, NIRS-based methodologies will likely allow more widespread clinical application of autoregulation monitoring in patients, enabling blood pressure to be individualized during surgery. The purpose of this study was to determine the effects of HCA on CBF autoregulation measured continuously during surgery with NIRS methods. We hypothesized that HCA would impair autoregulation compared with that measured before CPB and that of control patients undergoing aortic surgery without HCA.

Patients and Methods

This study was approved by The Johns Hopkins Medical Institutions Investigational Review Board, and all enrolled patients provided written informed consent. Eligible patients were those undergoing elective ascending or descending aortic replacement surgery with or without coronary artery bypass graft and/or valve surgery with possible HCA. Patients who had emergency surgery or preexisting chronic kidney disease that required dialysis were excluded.

Perioperative Care

Blood pressure was measured via a radial artery catheter and nasal temperature was monitored in all patients as routine institutional care. For surgery involving the ascending aorta, blood pressure was measured via the left radial artery while the right radial artery blood pressure was monitored when surgery involved the descending aorta. The transducers were kept level with the heart and zeroed before anesthesia induction. Blood pressure was monitored with a standard operating room hemodynamic monitor (General Electric, Solar 8000i, General Electric Medical Systems, Milwaukee, WI). Anesthesia was induced and maintained with midazolam, fentanyl, and isoflurane with pancuronium or vecuronium given for skeletal muscle relaxation. Isoflurane was administered during CPB via the membrane oxygenator and maintained at <1.0%. Non-pulsatile CPB was initiated with a non-occlusive roller pump, a membrane oxygenator, and 27- μ m arterial line filters and maintained at a flow rate between 2.0 and 2.4 L/min/m² with α -stat pH management. Gas flow to the oxygenator during CPB was adjusted to maintain normocarbia based on continuous in-line arterial blood gas monitoring calibrated at least every hour with arterial blood gas measurements. Sodium bicarbonate was given if needed to treat metabolic acidosis. Antegrade selective cerebral perfusion was at 500 ml/min. Blood pressure targets and rewarming rate during CPB were managed based on standard institutional clinical care.

Autoregulation Monitoring

All patients had left- and right-sided frontal rScO₂ monitored with NIRS (INVOS, Somanetics, Inc., Boulder, CO). Arterial blood pressure from an indwelling radial artery cannula was digitized and processed with a personal computer using ICM+ software (University of Cambridge, Cambridge, UK) by methods described previously (10, 13–16). Digital rScO₂ signals were processed directly with the same software. Signals were then filtered as non-overlapping 10-second average values that were time-integrated, a method that is equivalent to applying a moving average filter with a 10-second time window and resampling at 0.1 Hz. Through this process, high-frequency signals such as those from respiration and heart rate were eliminated; oscillations and transients that occur below 0.05 Hz were removed as well. Signals were further high-pass filtered with a DC cut-off set at 0.003 Hz to eliminate slow drifts associated with hemodilution, blood transfusions, cooling, and rewarming.

A continuous, moving Pearson correlation coefficient between MAP and rScO₂ was calculated to generate the cerebral oximetry index (COx). Consecutive, paired, non-overlapping 10-second averaged values over 300 seconds' duration were used for each calculation, incorporating 30 data points. When autoregulation is intact, MAP and rScO₂ are not correlated and COx approaches 0. When autoregulation is impaired, COx approaches 1, indicating that CBF is pressure passive. Based on prior studies, we defined the lower limit of autoregulation (LLA) as that MAP where COx increased from <0.3 to 0.3 (10, 17). An example of an autoregulation recording is shown in Figure 1.

Surgery

Patients were treated with standard surgical techniques that included ascending aortic, axillary, or femoral artery cannulation for CPB. The decision to use HCA was determined at the time of surgery based on whether aortic cross clamping could be achieved without compromise of the cerebral vessels. Patients who received HCA were administered a standard dose of steroid for cerebral protection and had ice packed around their head. The use of SACP via the innominate artery was determined by the operating surgeon based on perceived complexity of aortic arch surgery. All patients were rewarmed with a maximal gradient of 10°C between nasopharyngeal and heat exchanger water temperature.

Patient Outcome

The patients were followed daily by clinical staff and trained research personnel who entered patient outcomes into a study database. The patients were specifically assessed for the presence of major organ morbidity or operative mortality. Operative death was defined as any death that occurred during the hospitalization in which the operation was performed, even if after 30 days, or any death that occurred after discharge from the hospital, but within 30 days of the procedure, unless the cause of death was clearly unrelated to the operation. Major organ morbidity included stroke, mechanical lung ventilation > 48 hours, low cardiac output syndrome (inotrope use > 24 hours or new requirement for intra-aortic balloon pump insertion), and acute kidney injury based on RIFLE criteria (18). The last in-hospital serum creatinine measurement (Roche Diagnostics, Indianapolis, IN) before surgery was considered to be baseline. The lower sensitivity of this assay is 0.1 mg/dL.

Data Analysis

For analysis of autoregulation data, the surgery was divided into three phases. The pre-CPB phase was before initiation of CPB, the cooling phase was from initiation of CPB to beginning of HCA or rewarming, and the rewarming phase was from termination of HCA or beginning of rewarming to termination of CPB. Right and left rScO₂ and COx values were combined and averaged for all patients. The COx values were categorized into 5-mmHg bins of MAP for determination of the lower limit of autoregulation (LLA). The LLA was defined as the highest MAP associated with a COx $\leq$ 0.3 as previously described (13, 14, 16). For patients whose COx was $\leq$ 0.3 at all MAP, the LLA was defined as the MAP with the lowest COx (17, 18). Rewarming rate was calculated as the quotient of difference in peak and nadir temperatures and duration of patient re-warming.

Continuous data were compared by analysis of variance (ANOVA) with Bonferroni's correction for multiple comparisons. Dichotomous data were compared by Fishers exact test. Nonparametric data were log transformed before analysis. Statistical analysis was performed with Stata software version 11 (StataCorp LP, College Station, TX).

Results

From May 2003 to August 2012, we monitored 25 patients undergoing surgery on the descending, ascending aorta and/or aortic arch. Details of the surgical procedures are listed in Table 1. Thirteen patients underwent HCA. In 6 of these patients, SACP was used during a portion of HCA. Demographics and other characteristics were similar for the two groups of patients except that previous cardiac surgery was more common and the duration of CPB longer for those undergoing HCA (Table 2).

There was no difference between groups in arterial pH, PaO₂, and PaCO₂, during cooling and rewarming phases of surgery (Table 3). Hemoglobin tended to be lower in the HCA group during the cooling phase of CPB compared with the non-HCA group ($p=0.051$). The results were similar in all phases between the two groups. Nadir temperature of the patients was $19.7 \pm 2.3^\circ\text{C}$ for those undergoing HCA and $28.1 \pm 2.0^\circ\text{C}$ for those without HCA ($p<0.001$). The duration of cooling was longer in the non-HCA group but the duration of rewarming longer in the HCA group. However, the rate of rewarming was not different between the HCA and non-HCA group. Three patients in the non-HCA group and 11 in the HCA group had peak temperature during rewarming $\geq 37^\circ\text{C}$ ($p=0.005$). Among patients who underwent HCA, arterial pH, PaO₂, PaCO₂, hemoglobin, MAP, and rScO₂ were similar during each phase of surgery between those who had SACP and those who did not. Major morbidity and operative mortality are shown in Table 4.

Average COx values in each phase are shown in Figure 2. Baseline COx did not differ between the HCA and non-HCA patients. During cooling, average COx in each group did not differ significantly from baseline or between groups. During rewarming, average COx increased in the non-HCA patients compared with baseline ($p=0.006$), but COx did not change significantly in the HCA group. Average COx in the non-HCA group was higher than that in the HCA group during rewarming. Four patients (31%) in the HCA group and 9 (75%) in the non-HCA group had average COx > 0.3 during rewarming ($p=0.047$). For patients who underwent HCA, average COx did not change significantly from baseline, regardless of whether they had SACP, during any phase of surgery (Fig. 3).

The LLAs during the different phases of surgery are shown in Figure 4. The LLA did not differ between groups before initiation of CPB. In the HCA group, the LLA tended to decrease during the cooling phase of surgery compared with baseline, but it was not significantly different from baseline during rewarming. In the non-HCA group, the LLA did not alter during the cooling phase, but it was higher during the rewarming phase than at baseline. The LLA tended to be lower in the HCA group than in the non-HCA group during cooling ($p=0.053$), but there was no difference in the LLA between the two groups during rewarming ($p=0.392$).

Comment

In this study we found that CBF autoregulation measured with COx was not different during the cooling phase of CPB between patients who subsequently underwent HCA and those who did not. During rewarming, though, COx was higher in the non-HCA group than in the HCA group. Further, fewer patients in the HCA group than in the non-HCA group had abnormal COx during rewarming. There was no difference in the LLA between the surgical groups at baseline, but during cooling the LLA tended to be lower in the HCA group than in the non-HCA group. LLA did not differ between groups during rewarming. The use of SACP did not affect average COx of patients undergoing HCA. Thus, in contrast to our hypothesis, autoregulation was preserved in patients undergoing HCA. Further, perfusion measures used for managing patients undergoing HCA may be protective against impaired autoregulation during patient rewarming compared with aortic surgery without HCA.

In previous studies, we have shown that continuously correlating changes in rScO₂ against changes in MAP to generate an index of autoregulation is a clinically suitable surrogate of CBF for autoregulation monitoring (10, 14). NIRS does not distinguish arterial from venous O₂ saturation. Since most intracranial blood is venous blood, rScO₂ provides an indicator of the ratio of cerebral O₂ supply and demand. Focusing on low-frequency (20-second to 2-minute) changes in rScO₂ over short periods of time reduces the impact of changes in cerebral O₂ demand on the measurements, thus, providing an indicator of CBF. Monitoring COx provides a continuous assessment of autoregulation that is not subject to the motion or electrical artifact that occurs with transcranial Doppler monitoring. Thus, the use of COx allows for an assessment of CBF autoregulation throughout surgery, including before CPB, when the high use of electrocautery often prevents continuous transcranial Doppler monitoring.

Although CBF autoregulation is functional during normothermic CPB when alpha-stat pH management is used, it may become perturbed at extreme body temperatures (1). Greeley et al. (5) measured CBF using xenon-washout methods before, during, and after hypothermic CPB in neonates and children (age 1 day to 16 years) undergoing congenital heart surgery. During moderate hypothermic CPB (25°C to 32°C), CBF and MAP were not correlated, indicating functional autoregulation. In contrast to our findings, however, in the study by

Greeley et al. (5) CBF and MAP were correlated during deep hypothermic CPB (18°C to 22°C), indicating impaired autoregulation.

Our findings that COx was preserved during hypothermia prior to HCA, and the trend for a lower LLA in the HCA versus non-HCA patients, is consistent with our prior investigations. In a laboratory model of cardiac arrest, piglets resuscitated with mild hypothermia had a lower LLA than post-cardiac arrest normothermic animals.(19) In that study, COx was accurate in detecting the LLA compared with Doppler methods. These data along with our results support that cerebral vasodilatory responses to lowered blood pressure remains functional during hypothermia. We have previously noted that patient rewarming from mild hypothermic CPB is associated with a high frequency of impaired CBF autoregulation (3, 20). One explanation for this finding is inadvertent cerebral hyperthermia caused by the close proximity of CPB inflow at the base of the cerebral vessels or underestimation of brain temperature from systemic temperature monitoring. (21). Experimentally, cerebral hyperthermia leads to impaired CBF autoregulation, breakdown of the blood–brain barrier, and intracranial hypertension (22). Cerebral hyperthermia, though, would not seem to explain our findings of a higher COx during patient rewarming in the non-HCA group as the duration of re-warming and the number of patients with peak nasopharyngeal temperature > 37°C was actually higher in the HCA group. Further, the rate of patient re-warming was no different between groups, a finding supporting data from other showing the rate of rewarming does not influence autoregulation. (23). It is possible that aortic cannula positioning between the surgical groups (ie, closer to the cerebral vessels in the non-HCA group) or difference in patients cerebral vasculature for those requiring HCA versus no HCA for aortic reconstructive surgery explain the preserved autoregulation during re-warming in the former group.

We did not find that SACP influenced autoregulation after CPB which is in contrast to the findings of Neri et al. (6), who used transcranial Doppler to assess CBF autoregulation in adult patients undergoing elective aortic arch surgery. In that study CBF autoregulation immediately after surgery was functional in patients treated with SACP (n=25) but was impaired in patients undergoing surgery with retrograde cerebral perfusion (n=19) or HCA (n=23). Autoregulation testing methods as used by Greeley et al. (5) and Neri et al. (6) are able to ascertain only the presence or absence of functional CBF autoregulation; they are not capable of ascertaining dynamic aspects of autoregulation such as the LLA. Previously, we found that MAP at the LLA varies widely in adult patients undergoing coronary artery bypass graft and/or valve surgery, from 40 mmHg to 90 mmHg (15). It is possible that in some patients in prior studies, the MAP was less than the LLA. Such an occurrence would explain the observed impaired autoregulation as opposed to disturbed microvasculature control of CBF.

Our study is associated with several limitations, including the small number of study patients. The small sample size precludes our ability to determine whether a relationship exists between impaired autoregulation and adverse patient outcome. The use of HCA was not randomized but based on surgical considerations. This method might have led to some undetected bias in our findings. Our findings may only apply to patients undergoing surgery using a similar a temperature range, duration of HCA, cooling rate, duration of SACP, and rewarming rate as used in our study. Further, the accuracy of the autoregulation monitoring results are highly dependent on the accuracy and location of the arterial blood pressure measurements. Regardless, these limitations do not detract from the primary finding that autoregulation is similar during the cooling phase of surgery for patients who subsequently undergo HCA and those who do not. During rewarming, unlike those in the HCA group, patients not undergoing HCA exhibited a high prevalence of impaired autoregulation.

In conclusion, for patients undergoing aortic reconstructive surgery, HCA does not appear to adversely affect CBF autoregulation compared with standard cooling methods. Perfusion maneuvers associated with HCA may be protective against impaired autoregulation during rewarming compared with the non-HCA group.

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Disclosures

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Figure 1.

Intraoperative cerebral oximetry index (COx) recording. **A** is the time line of arterial pressure and regional cerebral oxygen saturation. **D** is the percentage of time spent at each 5- mmHg arterial blood pressure (ABP). **B:** Left (L) and **C:** right (R) COx represent the correlation between cerebral oxygen saturation and blood pressure. When blood pressure is outside the autoregulation limits, COx increases toward 1.

Figure 2.

Average cerebral oximetry index (COx) for patients undergoing surgery with and without hypothermic circulatory arrest (HCA). The box shows interquartile range (25th and 75th percentile) with a band representing the median. Whisker length represents 1.5 interquartile range. The dashed line at COx = 0.3 indicates the threshold for defining impaired autoregulation. Pre-CPB = before initiation of cardiopulmonary bypass (CPB); cooling = beginning of CPB to initiation of HCA or rewarming; rewarming = termination of HCA or beginning of rewarming to termination of CPB.

Figure 3.

Average cerebral oximetry index (COx) for patients who underwent hypothermic circulatory arrest (HCA) with and without antegrade selective cerebral perfusion (SACP). The box shows interquartile range (25th and 75th percentile) with a band representing the median. Whisker length represents 1.5 interquartile range. Data points not included between the whiskers are plotted as an outlier with a dot. The dashed line at COx = 0.3 indicates the threshold for defining impaired autoregulation. Pre-CPB = before initiation of cardiopulmonary bypass (CPB); cooling = beginning of CPB to initiation of HCA or rewarming; rewarming = termination of HCA or beginning of rewarming to termination of CPB.

Figure 4.

The lower limit of autoregulation (LLA) was compared for patients undergoing surgery with and without hypothermic circulatory arrest (HCA). The box shows interquartile range (25th and 75th percentile) with a band representing the median. Whisker length represents 1.5 interquartile range. Data points not included between the whiskers are plotted as an outlier with a dot. Pre-CPB = before initiation of cardiopulmonary bypass (CPB); cooling = beginning of CPB to initiation of HCA or rewarming; rewarming = termination of HCA or beginning of rewarming to termination of CPB.

Table 1

Surgical procedures for patients undergoing surgery with and without deep hypothermic circulatory arrest (HCA)

Procedure	All (n=25)	HCA (n=13)	Non-HCA (n=12)
Distal procedures			
Ascending aorta replacement	12	0	12
Ascending aorta + hemiarch replacement	5	5	0
Ascending aorta + arch replacement	6	6	0
Descending aorta replacement	2	2	0
Proximal procedures			
Supra-coronary graft	12	7	5
Aortic root replacement	11	4	7
Distal arch replacement	2	2	0
Associated procedures			
Aortic valve replacement	7	4	3
CABG	10	6	4

CABG = coronary artery bypass grafting.

Table 2

Medical information and operative data for patients undergoing aortic surgery with and without deep hypothermic circulatory arrest (HCA)

Variable	HCA (n=13)	Non-HCA (n=12)	<i>p</i> Value
Age (mean ± SD, years)	65±8	64±13	0.726
Male gender	7 (54%)	10 (83%)	0.202
Baseline creatinine (mg/dL)	0.96±0.19	0.99±0.26	0.747
Baseline eGFR (ml×min ⁻¹ ×1.73 m ⁻²)	79.6±30.2	82.2±6.2	0.810
Prior stroke	1 (8%)	2 (17%)	0.593
COPD	2 (15%)	0	0.480
Coronary artery disease	4 (31%)	5 (42%)	0.688
Peripheral vascular disease	2 (15%)	1 (8%)	1.000
Hypertension	10 (77%)	11 (92%)	0.593
Diabetes	2 (15%)	4 (33%)	0.378
Congestive heart failure	1 (8%)	0	1.000
Prior myocardial infarction	1 (8%)	0	1.000
Preoperative LVEF (% , mean ± SD)	53.1±14.7	55.4±7.8	0.628
Prior cardiac surgery	7 (54%)	1 (8%)	0.030
Preoperative medication			
Aspirin	10 (77%)	8 (67%)	0.673
Beta receptor blocking drugs	12 (92%)	7 (58%)	0.073
ACE-I	6 (46%)	5 (42%)	1.000
Statins	8 (62%)	7 (58%)	1.000
Operative data			
Duration of CPB (min, mean ± SD, range)	214±55 (132 to 306)	145±36 (90 to 224)	0.001
Duration of clamp (min, mean ± SD, range)	96±63 (75 to 181)	91±23 (49 to 130)	0.782
Duration of HCA (min, mean ± SD, range))	15±3 (9 to 33)		
Duration of SACP (min, mean ± SD, range)	11±5 (5 to 55)		

ACE-I = angiotensin converting enzyme inhibitors; COPD = chronic obstructive pulmonary disease; CPB = cardiopulmonary bypass; CVA = cerebral vascular accident; eGFR = estimated glomerular filtration rate; LVEF = left ventricular ejection fraction; SACP = antegrade selective cerebral perfusion.

Table 3

Intraoperative laboratory and other data for patients undergoing surgery with or without hypothermic circulatory arrest (HCA)

Variable/Phase	HCA (n=13)	Non-HCA (n=12)	<i>p</i> Value
pH			
Pre-CPB	7.43±0.05	7.43±0.04	0.797
Cooling	7.36±0.03	7.38±0.03	0.151
Rewarming	7.38±0.02	7.38±0.02	0.427
PaCO ₂ (mmHg)			
Pre-CPB	36.8±6.8	36.4±4.3	0.879
Cooling	44.5±2.3	43.2±2.8	0.208
Rewarming	39.7±2.2	41.3±2.6	0.105
PaO ₂ (mmHg)			
Pre-CPB	357.4±52.9	332.7±62.8	0.297
Cooling	275.4±46.0	257.3±21.7	0.225
Rewarming	254.0±24.1	258.9±33.9	0.679
Hemoglobin (g/dL)			
Pre-CPB	11.0±1.9	11.8±0.9	0.180
Cooling	9.2±1.5	10.2±0.7	0.051
Rewarming	8.9±0.7	9.3±1.3	0.430
MAP (mmHg)			
Pre-CPB	82.4±15.9	79.5±7.3	0.567
Cooling	69.6±15.1	73.7±5.1	0.373
Rewarming	70.5±15.1	67.2±6.9	0.492
rScO ₂			
Pre-CPB	67.5±11.9	67.3±9.4	0.960
Cooling	62.4±13.4	55.9±8.7	0.183
Rewarming	58.8±12.3	52.4±8.7	0.161
Temperature (°C)			
Temperature nadir (range)	19.7±2.3 (16.7 to 25.3)	28.1±2.0 (24.9 to 31.8)	<0.001
Temperature peak (range)	37.2±0.4 (36.3 to 37.5)	36.6±0.6 (35.3 to 37.4)	0.171
Duration (min)			
Cooling	61.4±27.6	85.3±19.0	0.020
Rewarming	120.6±38.1	56.7±15.9	<0.001
Rewarming rate (°C/min)	0.16±0.07	0.16±0.05	0.890

CPB = cardiopulmonary bypass; Cooling = beginning of CPB to initiation of HCA or rewarming; MAP = mean arterial blood pressure; Pre-CPB = before initiation of CPB; Rewarming = termination of HCA or beginning of rewarming to termination of CPB; rScO₂ = regional cerebral oxygen saturation.

Table 4

Postoperative outcomes for patients undergoing surgery with or without hypothermic circulatory arrest (HCA).

Variable	HCA (n=13)	Non-HCA (n=12)	<i>p</i> Value
Stroke	1 (8%)	2 (17%)	0.593
Delirium	3 (23%)	1 (8%)	0.593
Atrial fibrillation	5 (38%)	5 (42%)	1.000
Acute kidney injury	5 (38%)	7 (58%)	0.684
Mechanical ventilation > 48 hours	3 (22%)	1 (8%)	0.593
Low cardiac output syndrome	2 (15%)	0	0.480
Postoperative hospital stay (days, mean $\pm$ SD)	11 $\pm$ 6	7 $\pm$ 3	0.073
Operative death	1 (8%)	0	1.000

Acute kidney injury was defined by RIFLE criteria; low cardiac output syndrome was defined as inotrope use > 24 hours or new requirement for intra-aortic balloon pump insertion; operative death was defined as any death that occurred during the hospitalization in which the operation was performed, even if after 30 days, or any death that occurred after discharge from the hospital, but within 30 days of the procedure, unless the cause of death was clearly unrelated to the operation.