Low-flow antegrade cerebral perfusion attenuates early renal and intestinal injury during neonatal aortic arch reconstruction

Selma O. Algra, MD,^a Antonius N. J. Schouten, MD,^b Wim van Oeveren, PhD,^c Ingeborg van der Tweel, PhD,^d Paul H. Schoof, MD,^a Nicolaas J. G. Jansen, MD,^e and Felix Haas, MD^a

Objective: Deep hypothermic circulatory arrest (DHCA) and antegrade cerebral perfusion (ACP) are 2 cardiopulmonary bypass strategies mainly used in aortic arch reconstructions. It has been suggested that during ACP, abdominal organs are better protected than during DHCA owing to partial perfusion via collaterals. We tested this hypothesis using intraoperative near-infrared spectroscopy (NIRS), lactate measurements, and biomarkers for early abdominal injury in neonates undergoing complex aortic arch repair.

Methods: Neonates scheduled for aortic arch reconstruction via median sternotomy between 2009 and 2011 were randomized to either DHCA or ACP. During surgery, regional oxygen saturations of the abdomen were monitored using NIRS. Immediately after DHCA or ACP, lactate concentrations from the inferior vena cava were compared with those from the arterial cannula. Postoperatively, biomarkers for early abdominal organ injury were measured in urine.

Results: Twenty-five neonates were analyzed (DHCA, n = 12; ACP, n = 13). Procedures were performed at 18°C, and ACP flow was set at 35 to 50 mL · kg⁻¹ · min⁻¹. Median abdominal NIRS value during DHCA was 31% (IQR, 28%-41%) whereas during ACP it was 56% (IQR, 34%-64%; *P* < .01 between groups). Immediately after DHCA, median lactate from the inferior vena cava was 4.2 mmol/L (IQR, 3.3-5.3 mmol/L) compared with 3.1 mmol/L (IQR, 2.9-4.4 mmol/L) after ACP (*P* = .03). Postoperatively, biomarkers for renal and intestinal damage (glutathione s-transferase and intestinal fatty acid binding protein, respectively) were higher in the DHCA group than for the ACP group (*P* = .03, *P* = .04, respectively).

Conclusions: These results substantiate earlier suggestions that ACP provides more abdominal organ protection than DHCA in neonates undergoing aortic arch reconstruction. (J Thorac Cardiovasc Surg 2012;144:1323-8)

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Deep hypothermic circulatory arrest (DHCA) and antegrade cerebral perfusion (ACP) are 2 cardiopulmonary bypass (CPB) strategies applied in neonatal aortic arch repair. DHCA inherently results in full-body ischemia, whereas in ACP, the brain is selectively perfused at a low flow via the

innominate artery. Most studies are focused on the neurologic effects of either technique.^{1,2} However, abdominal organ functions also deserve attention inasmuch as postoperative renal function, for instance, is closely related to general postoperative recovery.³ Recently, we⁴ have shown that duration of postoperative recovery increases with longer duration of DHCA, whereas duration of ACP has no effect. It is thought that this is due to partial perfusion of the viscera through collaterals during ACP.⁵⁻⁸ Others have reported evidence of regional blood flow by abdominal near-infrared spectroscopy (NIRS) or blood pressure measurements in the abdominal or femoral arteries.^{5,7,8} Still, to date, the protective effect of ACP has remained a speculation, inasmuch as abdominal organ injury has not been directly assessed perioperatively.

Various organ-specific biomarkers have proved useful to estimate the extent of abdominal organ injury at an early time point after cardiac surgery or other intensive care settings.⁹ For renal injury, neutrophil gelatinase-associated lipocalin (NGAL) is the most widely reported marker; others include kidney injury molecule-1 (KIM-1), liver fatty acid binding protein (L-FABP), glutathione s-transferase (GST) and *N*-acetyl-β-D-glucosaminidase (NAG).¹⁰⁻¹⁷ For intestinal injury, intestinal fatty acid binding protein (I-FABP) is an established early biomarker.^{18,19}

From the Departments of Pediatric Cardiothoracic Surgery,^a Anesthesiology, Intensive Care and Emergency Medicine,^b Biostatistics,^d Pediatric Intensive Care,^c University Medical Center Utrecht, Utrecht, The Netherlands; and HaemoScan,^e Groningen, The Netherlands.

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Address for reprints: Selma O. Algra, MD, PO Box KG.01.319.0, UMC Utrecht, Lundlaan 6, 3584 EA Utrecht, The Netherlands (E-mail: s.o.algra@umcutrecht.nl). 0022-5223/\$36.00

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Abbreviations and Acronyms

ACP	= antegrade cerebral perfusion
CPB	= cardiopulmonary bypass
DHCA	= deep hypothermic circulatory arrest
GST	= glutathione s-transferase
I-FABP	= intestinal fatty acid binding protein
IQR	= interquartile range
KIM-1	= kidney injury molecule-1
L-FABP	= liver fatty acid binding protein
NAG	= <i>N</i> -acetyl- β -D-glucosaminidase
NGAL	= neutrophil gelatinase-associated lipocalin
NIRS	= near-infrared spectroscopy

In this study, we assessed the above-named biomarkers of early abdominal injury in neonates undergoing aortic arch reconstructions, before and after surgery. Furthermore, abdominal NIRS and lactate measurements were performed intraoperatively to estimate abdominal perfusion. We hypothesised that ACP would provide more abdominal perfusion and consequently result in less renal and intestinal injury than DHCA.

METHODS

Patients and Surgical Procedures

The current study was performed as part of a prospective randomized controlled trial comparing the neurologic effects of DHCA and ACP (clinicaltrials.gov number NCT01032876). In the subgroup reported here, data on abdominal perfusion were collected; these consisted of intraoperative abdominal NIRS monitoring and lactate measurements and preoperative and postoperative urine analysis of biomarkers for early abdominal injury. The institutional medical ethics committee approved the study and all parents gave informed consent for enrollment. Patients in whom a congenital syndrome was suspected were not eligible for inclusion in the study.

In all patients, surgery was performed through a median sternotomy and standard cannulation techniques with double venous cannulation were applied. In case of interrupted aortic arch, double cannulation of the distal ascending aorta and the pulmonary trunk was performed. CPB was performed using alpha-stat strategy, and patients were cooled for a minimum of 20 minutes to a nasopharyngeal temperature of 18°C. ACP was performed directly by advancing the arterial cannula into the innominate artery. In the case of a Norwood procedure with a modified Blalock-Taussig shunt, the shunt was anastomosed to the innominate artery before aortic arch reconstruction and the shunt was used to deliver ACP. A target flow rate of 25% (35-50 mL · kg⁻¹ · min⁻¹) was used with a perfusate temperature of 18°C and right radial pressures not exceeding 40 mm Hg. Depending on the individual anatomic situation, the aortic arch was reconstructed by direct end-to-end or end-to-side anastomosis, reverse subclavian flap and patch plasty, or patch plasty alone. All procedures were performed by a single surgical team.

NIRS Measurements

Throughout the perioperative period, regional saturations of the frontal cerebrum and the abdomen were estimated using NIRS. For somatic measurement, the electrode (size Pediatric, INVOS, Somanetics, Troy, Mich)

was placed longitudinally on the left flank, just caudal of the costal margin. The electrode positioning was verified using ultrasound in the first 10 patients, all showing placement over the left kidney. Mean values of the following 4 periods were calculated: preoperative (minimum of 6 hours of monitoring), deep hypothermic full-flow CPB, during DHCA or ACP, and during the first 30 minutes after reinstitution of normal CPB.

Lactate Measurements

When aortic arch reconstruction was completed and full-body CPB re-instituted, blood samples were simultaneously drawn from the arterial cannula and the snugged inferior venous cannula within the first minute of reperfusion. After the inferior venous cannula had been temporarily clamped and the first 10 mL of blood discarded (as this approximates the dead space of the cannula), a sample of 0.5 mL of blood was drawn from the inferior vena cava for determination of lactate concentration.

Urine Analysis for Biomarkers

Urine samples were collected preoperatively and postoperatively. Preoperatively, urine was collected before initiation of CPB, and the postoperative time point consisted of urine produced during the second hour after skin closure. NGAL, KIM-1, L-FABP, and I-FABP were measured using enzyme-linked immunosorbent assay. GST (total of α and π) and NAG were measured using colorimetric enzymatic assay. Biomarkers of organ injury were assessed at HaemoScan, Groningen, The Netherlands. Markers were additionally expressed as a ratio of urine production in milliliters per kilogram per hour to correct for dilution of urine.²⁰

Statistical Analysis

Data in text are stated as median (interquartile range [IQR]) or number of patients (percentage of group) unless noted otherwise. Differences in continuous variables between DHCA and ACP groups were compared using the Mann-Whitney *U* test. SignalBase version 6.76 (University Medical Center Utrecht, The Netherlands) was used for calculation of NIRS values. SPSS version 15.0 (SPSS, Inc, Chicago, Ill) was used for statistical analyses and GraphPad Prism version 5.03 (GraphPad Software, La Jolla, Calif) was used for graphic figures.

RESULTS

Patients and Surgical Data

Specific diagnoses and surgical data are listed in Table 1. Eight neonates underwent univentricular repair, whereas the other 17 underwent biventricular repair. According to the randomization protocol, 12 neonates underwent surgery with DHCA and 13 neonates with ACP.

One patient from the DHCA group died within 30 days postoperatively. Low cardiac output syndrome and renal failure developed, which required peritoneal dialysis at 18 days postoperatively. The patient died 1 week later. None of the other patients had any abdominal complications.

Systemic Saturation and Cerebral NIRS

The preoperative oxygenation status was similar in both groups. Before the start of CPB, the median systemic saturation in the DHCA group was 97% (IQR, 93%-100%) and for the ACP group this was 98% (IQR, 95%-99%). Regarding preoperative cerebral NIRS values, the DHCA group had a median of 59% (IQR, 54%-67%) vs a median of 62% (IQR, 54%-67%) for ACP. At deep hypothermic full flow, the DHCA group had a median cerebral NIRS

TABLE 1. Patient characteristics and operative data

	DHCA (n = 12)	ACP (n = 13)
Age at operation (d)	9 (8-11)	9 (8-23)
Weight at operation (kg)	3.6 (3.2-3.8)	3.6 (2.5-3.7)
Gestational age at birth (wk)	39 (38.3-40.0)	39 (38.3-40.0)
Cardiac diagnoses, biventricular repair (n = 17):		
Hypoplastic aortic arch/CoA, plus:		
No intracardiac defects	0	1
VSD	1	3
ASD	0	1
cAVSD	1	0
TGA	1	0
Aortic valve stenosis	0	1
Double-outlet right ventricle	1	1
Interrupted aortic arch, plus:		
VSD, ASD	0	1
Severe LVOTO (Ross-Konno procedure)	1	0
TGA	1	0
Hypoplastic left heart complex*	0	3
Univentricular repair (n = 8):		
Hypoplastic left heart syndrome	4	1
Double-inlet left ventricle	0	1
Tricuspid atresia	2	0
CPB data:		
Cooling duration (min)	35 (30-40)	30 (29-38)
Duration of DHCA or ACP (min)	33 (28-38)	39 (32-49)
Total CPB duration	167 (142-266)	161 (129-169)
ACP flow rate (mL · kg ⁻¹ · min ⁻¹)		46 (41-49)
Nasopharyngeal temperature during DHCA/ACP (°C)	17.3 (16.5-18.0)	17.7 (17.4-18.3)
Rectal temperature during DHCA/ACP (°C)	20.7 (20.0-21.8)	20.7 (19.4-21.9)

Values shown in median (interquartile range) or number of patients. *DHCA*, Deep hypothermic circulatory arrest; *ACP*, antegrade cerebral perfusion; *CoA*, coarctation of the aortic arch; *VSD*, ventricular septal defect; *ASD*, atrial septal defect; *cAVSD*, complete atrioventricular septal defect; *TGA*, transposition of the great arteries; *LVOTO*, left ventricular outflow tract obstruction; *CPB*, cardiopulmonary bypass. *Hypoplastic left heart complex was defined as an underdevelopment of the left heart with significant hypoplasia of the left ventricle and hypoplasia of the aortic and/or mitral valve, ascending aorta and aortic arch, but in the absence of intrinsic valvular stenosis or atresia.²¹

of 80% (IQR, 70%-92%), which was 79% (IQR, 72%-85%) in the ACP group. During DHCA a median of 51% was observed (IQR, 49%-54%) vs 80% (IQR, 70%-88%) during ACP. During reperfusion, saturations were 74% (IQR, 71%-79%) for the DHCA group and 73% (IQR, 66%-78%) for the ACP group.

Abdominal NIRS

Abdominal NIRS measurements are depicted in Figure 1. Before surgery, abdominal NIRS values were similar in the 2 groups, with a median of 53% (IQR, 49%-59%) in the DHCA group and 56% (IQR, 48%-72%) in the ACP group. At deep hypothermic full-flow CPB, the DHCA

FIGURE 1. Abdominal near-infrared spectroscopy (NIRS) values are lower during deep hypothermic circulatory arrest (DHCA) than during antegrade cerebral perfusion (ACP) (* $P < .01$). Values are shown in medians and interquartile ranges (boxes) and minimum and maximum values (whiskers). *ACP*, Antegrade cerebral perfusion; *DHCA*, deep hypothermic circulatory arrest; *NIRS*, near-infrared spectroscopy.

group had a median saturation of 89% (IQR, 79%-94%), which was 77% (IQR, 68%-92%) in the ACP group. During DHCA, abdominal NIRS values decreased to a median of 31% (IQR, 28%-41%), which was significantly lower than during ACP (median, 56% [IQR, 36%-64%]; $P < .01$). During the first 30 minutes after reinstitution of normal CPB, the DHCA group had a median value of 74% (IQR, 67%-87%) whereas this was 83% (IQR, 76%-91%) in the ACP group.

Lactate Measurements

Lactate measurements were collected in all but 3 neonates (DHCA, n = 11; ACP, n = 11) and are shown in Figure 2. Lactate concentrations from the arterial cannula and from the inferior vena cava were compared. Arterial lactate values were similar between DHCA and ACP

FIGURE 2. Arterial lactate concentrations are similar between deep hypothermic circulatory arrest (DHCA) and antegrade cerebral perfusion (ACP), whereas lactate concentrations from the inferior vena cava (IVC) are significantly higher after DHCA than after ACP (* $P = .03$). Values are shown in medians and interquartile ranges (boxes) and minimum and maximum values (whiskers).

TABLE 2. Abdominal biomarker results

	DHCA		ACP		<i>P</i> value postop (DHCA vs ACP)
	Preop (n = 9)	Postop (n = 11)	Preop (n = 10)	Postop (n = 12)	
Absolute urinary concentrations					
Renal injury					
NGAL	89 (4.6-149)	185 (92-235)	27 (9.2-60)	47 (24-117)	.07
GST	5.2 (2.4-6.0)	7.2 (5.3-7.9)	5.4 (2.0-6.7)	3.8 (2.2-6.1)	.03
L-FABP	128 (55-426)	262 (43-421)	83 (34-312)	132 (22-607)	.61
NAG	8.6 (0.9-18)	39 (9.7-67)	8.1 (2.7-20)	24 (6.2-53)	.50
KIM-1	2.7 (0.7-6.3)	1.5 (0.6-10.0)	1.1 (0.4-2.3)	0.6 (0.2-2.8)	.14
Intestinal injury					
I-FABP	11 (6.7-90)	82 (30-180)	15 (7.9-38)	11 (0.0-101)	.04
Results corrected for urine output					
Renal injury					
NGAL	19 (1.2-78)	119 (84-136)	11 (5.3-22)	14 (5.8-53)	<.01
GST	1.2 (0.5-3.7)	4.7 (2.8-5.9)	0.9 (0.3-2.4)	1.4 (0.3-2.5)	.02
L-FABP	83 (13-280)	271 (39-541)	37 (5.6-101)	19 (9.6-88)	.03
NAG	3.8 (0.1-7.6)	26 (4.4-61)	2.3 (1.1-5.6)	5.1 (1.5-26)	.11
KIM-1	0.5 (0.1-4.3)	1.4 (0.2-7.8)	0.4 (0.2-1.0)	0.4 (0.03-1.0)	.05
Intestinal injury					
I-FABP	6.6 (1.5-65)	19 (59-134)	3.9 (0.00-13)	1.5 (0.00-39)	.01
Urine output (mL · kg ⁻¹ · h ⁻¹)	4.2 (2.4-6.8)	1.5 (0.8-3.1)	4.0 (2.4-5.8)	2.8 (1.4-6.3)	.10

Values are shown in median (interquartile range). DHCA, Deep hypothermic circulatory arrest; ACP, antegrade cerebral perfusion; NGAL, neutrophil gelatinase-associated lipocalin (ng/mL); GST, glutathione s-transferase (U/mL); L-FABP, liver fatty acid binding protein (ng/mL); NAG, N-acetyl- β -D-glucosaminidase (mU/mL); KIM-1, kidney injury molecule-1 (ng/mL); I-FABP, intestinal fatty acid binding protein (ng/mL).

(median DHCA, 2.8 mmol/L [IQR, 2.2-3.4 mmol/L]; median, ACP, 2.9 mmol/L [IQR, 2.4-3.9 mmol/L]). After DHCA, lactate from the inferior vena cava had a median of 4.2 mmol/L (IQR, 3.3-5.3 mmol/L), which was significantly higher than the caval lactate in the ACP group (median, 3.1 mmol/L [IQR, 2.9-4.4 mmol/L]; $P = .03$).

Abdominal Biomarkers

Biomarkers of renal and intestinal injury were measured preoperatively in 19 neonates (DHCA, $n = 9$; ACP, $n = 10$) and postoperatively in 23 neonates (DHCA, $n = 11$; ACP, $n = 12$). Results are listed in Table 2. The absolute concentrations of the renal marker GST and intestinal marker I-FABP were significantly higher postoperatively in the DHCA group compared with the ACP group ($P = .03$ and $P = .04$, respectively). Regarding the other markers of renal injury (NGAL, L-FABP, NAG, and KIM-1), the difference of postoperative values between DHCA and ACP did not reach statistical significance ($P = .07$, $P = .61$, $P = .50$, and $P = .14$, respectively). When correcting for urine output at the time of sampling, all markers except NAG and KIM-1 were significantly higher postoperatively in the DHCA group than the ACP group (NGAL, $P < .01$; GST, $P = .02$; L-FABP, $P = .03$; NAG, $P = .11$; KIM-1, $P = .05$; and I-FABP, $P = .01$). The median postoperative urine output itself was 1.5 mL · kg⁻¹ · h⁻¹ in the DHCA group vs 3.0 mL · kg⁻¹ · h⁻¹ in the ACP group ($P = .10$). Stratified by univentricular and biventricular repair, the median and ranges for the various biomarkers are listed in Table E1.

Serum creatinine and blood urea nitrogen levels were available for a limited number of patients preoperatively (DHCA, $n = 12$; ACP, $n = 12$) and postoperatively (DHCA, $n = 7$; ACP, $n = 6$). For blood urea nitrogen, a significant difference between postoperative levels was detected ($P = .03$) whereas for creatinine this was $P = .05$. Results are listed in Table E2.

DISCUSSION

The results of the current study substantiate that in neonates undergoing complex aortic arch repair, abdominal organs are better protected by low-flow ACP than by DHCA. During DHCA, abdominal NIRS values were lower and lactate concentrations higher than during ACP, likely resulting in the increased concentrations of renal and intestinal organ damage markers after surgery.

The current findings confirm earlier suggestions in literature. Pigula and associates⁸ were the first to measure evidence of flow in the abdominal aorta during ACP. Since then, others have assessed abdominal NIRS trends during ACP and have found that NIRS values rise with increasing ACP flow rate.^{5,7,22} Recently, we⁴ have added to the literature that DHCA duration during aortic arch reconstruction is linearly related to the duration of postoperative recovery, whereas ACP is not. Taken together, these findings strongly point toward the phenomenon of abdominal perfusion during ACP.

We intended to assess markers of organ injury as close to the insult as possible. This explains the choice for the

biomarkers used in this study, instead of the more widely known markers such as creatinine and urea for renal function. The latter markers are known to measure organ function and are generally raised 1 to 3 days after surgery, whereas the current biomarkers in this study are able to detect early organ injury, making factors such as low cardiac output less likely to obscure results.⁹ Renal injury was assessed by 5 different biomarkers. Of these, NGAL has generally been researched most extensively. Recently, 2 large studies validated the marker in the pediatric cardiac surgery population and observed that acute kidney injury could be detected by NGAL as early as 2 hours after surgery with mean values of 300 to 500 ng/mL.^{10,11} Krawczeski and colleagues¹¹ specifically calculated a cutoff point for the neonatal population at 185 ng/mL. When this is applied to our cohort, after surgery, 5 of the 12 in the DHCA group would find themselves above this threshold vs 2 of 13 in the ACP group. When comparing the concentrations of the current group of neonates with those reported for all 5 renal biomarkers used in this study, some of the organ injury markers are already elevated in the patients preoperatively, likely reflecting the compromised cardiac situation. Postoperatively, the values in the DHCA group indicate that substantial renal injury has occurred, whereas this is much less the case after ACP.

Previously published articles concerning renal biomarkers have mostly reported absolute urinary concentrations in their studies.¹⁰⁻¹⁷ However, correction to the urine production at the time of sampling has recently been stated to be the most reliable way of assessing renal injury.²⁰ Inasmuch as differences between DHCA and ACP became especially apparent in the analysis corrected for urine production, this confirms that DHCA results in more renal injury than ACP.

Intestinal injury was estimated using I-FABP, which has been used in both adults and neonates to determine intestinal ischemia.^{18,19} Compared with these reports, the preoperative values are acceptable whereas the postoperative values after DHCA are among the highest reported, indicating that the intestinal injury is substantial after DHCA. In contrast, after ACP, the values seem to be in the normal range.

Abdominal NIRS values during ACP showed a large variation between patients. This is likely due to both a varying degree of collaterals and a varying duration of ACP. Consequently, this does indicate that abdominal perfusion cannot be *guaranteed* in the individual patient during ACP, but at a group level, ACP does seem to provide protection from ischemic renal and intestinal injury. The lactate measurements support this notion, inasmuch as these were generally increased in the DHCA group, whereas they remained unchanged in the ACP group. Neonates with aortic arch obstructions are probably ideal candidates for the advantageous effects of ACP, inasmuch as their anatomy will have stimulated the growth of collaterals traveling from

the aortic arch and the innominate arteries, via the mammary and epigastric arteries, to the abdominal viscera.²³⁻²⁵

This study has important limitations that deserve consideration. First, apart from NGAL, the various biomarkers have not been validated in this specific population and the limited sample size in the current study prevents this. However, as these markers are known to show early injury, we chose to primarily assess these instead of the more traditional markers. These markers are currently as close to the injury as one can get. Ultimately, histologic assays (in animal models) can only confirm specific organ injury; however, a significant limitation to the use of animals is the different collateralization pattern. The second important limitation is the small sample size, which will have resulted in a lower power to detect statistical differences between the DHCA and ACP groups. Furthermore, despite the randomization for DHCA and ACP, the proportion of univentricular and biventricular patients between the 2 groups is unbalanced. To minimize the impact of a low cardiac output state on biomarker results, we collected urine samples very shortly after surgery.

In conclusion, the results presented here show that during neonatal aortic arch reconstruction, ACP provides more abdominal perfusion than does DHCA. As a consequence, this likely has a protective effect on abdominal organs. The current results explain findings in previous studies showing an adverse effect of DHCA, but not ACP, on early postoperative recovery.

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TABLE E1. Abdominal biomarkers: Univentricular and biventricular repairs

	DHCA		ACP	
	Preoperative (2V, n = 5; 1V, n = 4)	Postoperative (2V, n = 7; 1V, n = 4)	Preoperative (2V, n = 8; 1V, n = 2)	Postoperative (2V, n = 10; 1V, n = 2)
Absolute urinary concentrations				
NGAL				
2V	76 (4.0-222)	161 (26-797)	60 (21-168)	79 (27-126)
1V	85 (22-149)	218 (202-235)	(8.7-11)	(358-560)
GST				
2V	4.4 (0.00-5.8)	7.2 (6.4-7.9)	6.1 (4.2-11)	6.1 (1.7-11)
1V	6.5 (5.9-7.0)	7.4 (6.8-8.0)	(1.7-3.2)	(2.2-2.2)
L-FABP				
2V	128 (23-451)	371 (43-615)	236 (13-899)	313 (21-1093)
1V	323 (97-549)	420 (29-811)	(79-86)	(21-612)
NAG				
2V	9.3 (0.10-29)	31 (2.9-119)	13 (0.20-27)	22 (3.3-78)
1V	15 (0.00-31)	42 (13-70)	(1.7-5.7)	(29-48)
KIM-1				
2V	2.0 (0.22-6.5)	4.9 (0.18-13)	1.6 (0.04-8.2)	1.9 (0.02-4.2)
1V	2.5 (1.0-4.0)	9.3 (1.8-17)	(0.21-0.71)	(0.15-0.35)
I-FABP				
2V	40 (6.9-150)	147 (30-205)	19 (0.00-50)	8.9 (0.00-165)
1V	35 (0.00-70)	335 (79-592)	(32-36)	(6.3-198)
Results corrected for urine output				
NGAL				
2V	19 (0.61-84)	119 (53-1139)	15 (5.3-42)	27 (4.0-84)
1V	84 (3.2-165)	123 (112-134)	(2.0-5.5)	(23-373)
GST				
2V	1.2 (0.00-4.8)	5.9 (4.8-14)	1.9 (0.67-2.8)	1.6 (0.24-5.8)
1V	3.8 (1.0-6.6)	4.2 (3.8-4.5)	(0.74-0.85)	(0.14-1.5)
L-FABP				
2V	51 (5.3-335)	374 (39-742)	45 (3.2-346)	57 (9.5-336)
1V	312 (14-610)	277 (14-541)	(20-41)	(14-39)
NAG				
2V	3.8 (0.02-7.8)	31 (2.6-88)	3.1 (0.05-6.5)	5.1 (1.2-36)
1V	17 (0.00-34)	21 (8.9-33)	(0.40-2.9)	(1.9-32)
KIM-1				
2V	0.5 (0.03-5.4)	5.8 (0.12-9.8)	0.5 (0.01-2.3)	0.8 (0.00-1.2)
1V	2.3 (0.15-4.4)	4.6 (1.2-8.0)	(0.05-0.36)	(0.01-0.22)
I-FABP				
2V	9.0 (1.0-125)	133 (22-294)	3.9 (0.00-19)	2.8 (0.00-75)
1V	39 (0.00-78)	167 (53-282)	(8.8-17)	(0.40-132)
Urine output (mL · kg ⁻¹ · h ⁻¹)				
2V	4.8 (1.2-7.0)	1.1 (0.50-8.0)	4.5 (2.6-8.0)	3.0 (1.2-6.8)
1V	2.6 (0.9-6.8)	2.6 (1.5-3.8)	(1.75-1.95)	(0.25-8.0)
Serum markers				
	(2V, n = 6; 1V, n = 6)	(2V, n = 4; 1V, n = 3)	(2V, n = 10; 1V, n = 2)	(2V, n = 4; 1V, n = 1-2)
Creatinine				
2V	50 (36-78)	62 (47-70)	43 (24-59)	52 (41-59)
1V	60 (56-92)	73 (73-75)	(43-68)	(61-63)
BUN				
2V	3.1 (0.50-5.0)	3.1 (1.9-11)	1.8 (0.50-3.2)	2.3 (1.5-6.0)
1V	2.9 (1.6-5.8)	4.1 (2.8-5.5)	(3.7-4.0)	4.0

1V, Univentricular; 2V, biventricular; DHCA, deep hypothermic circulatory arrest; ACP, antegrade cerebral perfusion; NGAL, neutrophil gelatinase-associated lipocalin (ng/mL); GST, glutathione s-transferase (U/mL); L-FABP, liver fatty acid binding protein (ng/mL); NAG, N-acetyl-β-D-glucosaminidase (mU/mL); KIM-1, kidney injury molecule-1 (ng/mL); I-FABP, intestinal fatty acid binding protein (ng/mL); BUN, blood urea nitrogen.

TABLE E2. Serum markers of renal function

	DHCA		ACP		<i>P</i> value postoperative (DHCA vs ACP)
	Preoperative (n = 12)	Postoperative (n = 7)	Preoperative (n = 12)	Postoperative (n = 6)	
Creatinine	58 (46-69)	70 (54-73)	43 (39-55)	55 (45-60)	.05
BUN	2.9 (1.4-4.2)	3.6 (2.9-5.2)	2.0 (1.4-3.1)	2.3 (1.4-3.1)	.03

DHCA, Deep hypothermic circulatory arrest; *ACP*, antegrade cerebral perfusion; *BUN*, blood urea nitrogen.