A propensity score–matched comparison of deep versus mild hypothermia during thoracoabdominal aortic surgery

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Objective: By using deep hypothermic circulatory arrest and non–deep hypothermic circulatory arrest approaches, we examined the impact of distal ischemia time and temperature on intra-abdominal reversible adverse outcomes and permanent adverse outcomes during descending thoracic aortic and thoracoabdominal aortic aneurysm operations.

Methods: A retrospective review of all patients who underwent descending thoracic aortic and thoracoabdominal aortic aneurysm repair between January 2002 and December 2008 was undertaken, including relevant preoperative, intraoperative, and postoperative data, and followed by a propensity score–matched analysis. Of the total of 262 patients, 240 had data complete enough to permit analysis, and 90 were suitable for the propensity-matched study. Reversible adverse outcomes included renal failure, liver failure, and temporary hemodialysis. Permanent adverse outcomes included paraplegia, permanent hemodialysis, and 30-day mortality.

Results: Thirty-day mortality was 7.1% (17/240). Overall, reversible adverse outcomes developed in 40.8% of patients and permanent adverse outcomes developed in 10% of patients. The propensity score analysis identified statistically significant decreased odds of developing reversible adverse outcomes in patients undergoing deep hypothermic circulatory arrest (odds ratio, 0.32; confidence interval, 0.12–0.85). Specifically, significantly lower rates of acute renal failure (22% vs 46.4%, \(P = .03\)) and liver failure (17.8% vs 34.3%, \(P = .04\)) were observed in the deep hypothermic circulation arrest group compared with the non–deep hypothermic circulation arrest group. In addition, there were decreased odds of reversible adverse outcomes (odds ratio, 0.22; confidence interval, 0.06–0.79) developing in patients with a stage II elephant trunk procedure.

Conclusions: During descending thoracic aortic and thoracoabdominal aortic aneurysm repairs, the use of deep hypothermic circulatory arrest results in improved postoperative adverse outcome rates compared with non–deep hypothermic circulatory arrest techniques. The development of reversible adverse outcomes is strongly associated with the development of permanent adverse outcomes. (J Thorac Cardiovasc Surg 2012;143:186-93)

Despite recent advances in surgical techniques and organ protection strategies, descending thoracic aortic aneurysm (DTA) and thoracoabdominal aortic aneurysm (TAAA) repairs remain a therapeutic challenge to most cardiac and vascular surgeons. Patients with DTA and TAAA are typically high-risk surgical candidates because of advanced age and multiple comorbidities, such as chronic lung and cardiovascular disease.

Although endovascular repair has made recent strides in treating DTA and TAAA, open surgical repair remains the standard approach to treatment. Many perfusion techniques have been used for open surgeries, including clamp-and-sew, mild hypothermia with atriofemoral or femoral-femoral bypass, and deep hypothermic circulatory arrest (DHCA). Regardless of methodology, end-organ protection during these complex operations continues to be problematic.4,6

Proponents of DHCA champion its ability to decrease a tissue’s metabolic rate, which enhances organ protection from ischemia. Routine use of DHCA in DTA and TAAA repair has shown promising results in reports from high-volume aortic centers,7,8 but this technique is still used selectively. Currently, no data directly comparing the outcomes of DHCA with non-DHCA techniques during complex distal aortic surgery at the same institution have been reported. By using DHCA and non-DHCA approaches, we examined the impact of distal ischemia time (DIT) and temperature on intra-abdominal reversible adverse outcomes (RAOs) and permanent adverse outcomes (PAOs) after DTA and TAAA repair.

MATERIALS AND METHODS
A retrospective review of our institutional database disclosed 262 consecutive patients who underwent DTA and TAAA repair operations between January 2002 and December 2008. After excluding 6 patients with incomplete data (no record of DIT or temperature) and 22 patients on
preoperative hemodialysis, a total of 240 patients had complete data for analysis. The data for the excluded patients are shown in Appendix 1. The institutional review board approved this research; additional patient consent was not required.

Study Variables
DTA was defined as an aortic aneurysm exclusively in the thoracic cavity, and TAAA designates those aneurysms that fit into the Crawford classification. Preoperative imaging and intraoperative findings determined the extent of the repair. DIT was defined as circulatory arrest time plus the time required to restore distal perfusion. In certain cases in which visceral artery reimplantation was necessary, that time interval was added to the initial DIT. Emergency surgery was defined as an acute presentation requiring immediate surgical intervention. Aortic dissection was designated acute if the surgery was undertaken within 14 days of the initial tear and chronic if the operation occurred after 14 days. A patient was defined as having rupture if on thoracotomy a free blood or clot containing the bleed was discovered. Any previous thoracotomy or thoracoabdominal incision for aortic surgery resulted in a designation of reoperation. Preoperative renal failure was defined as a creatinine 2.5 mg/dL or greater on admission. Other preoperative variables included age, body mass index, history of smoking or chronic obstructive pulmonary disease, previous stroke, and hemodialysis.

Temporary postoperative hemodialysis, postoperative acute renal failure (more than twice the admission creatinine level), or postoperative liver failure (more than four times the admission hepatic transaminase level) were considered RAO. Elevated transaminases were used as a surrogate for malperfusion of the viscera because a lactate level is too nonspecific to monitor intestinal ischemia in the early postoperative period after complex aortic reconstruction. PAO included hemodialysis lasting 30 minutes to reduce the diaphragm and the bladder temperature was greater than 32°C. Although our protocol is to cool for 30 minutes to reduce the esophageal and bladder temperature maintained at less than 10°C until the esophageal temperature reached 35°C and the bladder temperature was greater than 32°C. Warming was usually accomplished with 1 hour of perfusion; during the last 15 or 20 minutes, partial bypass was frequently used to take advantage of improved warming with pulsatile perfusion. However, downward drift resulted in most patients leaving the operating room at esophageal and bladder temperatures of 32°C.

Non-DHCA techniques were conducted with bladder temperatures between 31°C and 33°C, effected by a cooling blanket. Distal perfusion was added, usually after a period of distal ischemia during which an open anastomosis was completed. In a few cases, there was no period of absolute distal ischemia because a clamp was applied distal to the aortic resection, and distal aortic perfusion was initiated immediately. For non-DHCA techniques, median minimum proximal pressure was 73 (range, 43–134; mean, 73.2 ± standard deviation 13.5), median maximum proximal pressure was 95 (range, 72–160; mean, 97.5 ± 14.1), median minimum distal pressure was 60 (range, 1–92; mean, 56.4 ± 16.5), and median maximum distal pressure was 85 (range, 50–140; mean, 85.2 ± 17.0). In general, distal bypass flows were in the range of 1.5 to 2 L/min. All patients were heparinized.

Surgical Management
Preoperative steroids (2 g of dexamethasone) and prophylactic antibiotics were given. Arterial cannulation was carried out through the femoral or axillary artery or the distal transverse arch/descending aorta. Venous cannulation was established with a wire directed catheter placed in the right atrium through the femoral vein and confirmed by tranesophageal echocardiogram.

DHCA was used in 77 of the 240 patients (32.1%) and effected by surface (cooling blanket) and perfusion cooling. The decision to use DHCA was prompted by technical considerations, often involving the feasibility and safety of clamping the aorta proximal to the repair. If DHCA was anticipated early in the procedure, the patient was cooled during the initial period of cardiopulmonary bypass (CPB). A minimum of 30 minutes of cooling was used. Patients who had DHCA instituted later in the operative procedure were maintained at a perfusion temperature of 20°C until approximately 15 minutes before DHCA, after which the blood temperature was lowered to 10°C. Adequate cerebral cooling was ensured in all cases by a jugular venous saturation greater than 95% and a bladder temperature of 12°C to 15°C. Although our protocol is to cool for 30 minutes to reduce the bladder temperature to 15°C, some patients required an additional 30 minutes of cooling. If the bladder temperature remained elevated after 60 minutes of cooling, the jugular bulb venous saturations were checked, and the surgeon determined whether DHCA could be initiated. In all patients for whom more than 20 minutes of DHCA was anticipated, the head was packed circumferentially in ice.

On completion of the proximal anastomosis, selective upper body perfusion was executed through a side-branch on the Hemashield graft or axillary artery with a flow rate of approximately 1 to 1.5 L/min and pressure of 55 to 60 mm Hg. Perfusion warming was carried out at the end of the procedure, with the gradient between the esophageal and blood temperature maintained at less than 10°C until the esophageal temperature reached 35°C and the bladder temperature was greater than 32°C. Warming was usually accomplished with 1 hour of perfusion; during the last 15 or 20 minutes, partial bypass was frequently used to take advantage of improved warming with pulsatile perfusion. However, downward drift resulted in most patients leaving the operating room at esophageal and bladder temperatures of 32°C.

Thoracic Aortic Aneurysm/Thoracoabdominal Aortic Aneurysm Repair Technique
The aneurysm was approached through a left thoracotomy or thoracoabdominal incision. If access to the abdominal aorta was necessary, the diaphragm was divided circumferentially. The aneurysm was dissected free from mediastinal and retroperitoneal tissues. The abdominal aorta and visceral arteries were accessed via a retroperitoneal approach. The intercostal and lumbar arteries were dissected and temporarily occluded in sequence. If motor evoked potentials (MEPs) and somatosensory evoked potentials (SSEPs) remained unchanged, the segmental vessels were sacrificed before opening the aneurysm to avoid backbleeding and possible steal from the spinal cord circulation. In general, in view of its importance in supporting spinal cord perfusion, clamping of the subclavian artery was avoided. The thoracic and epigastric arteries are also potentially important conduits into the collateral network of vessels supplying the spinal cord and were therefore also preserved by performing the thoracoabdominal incisions lateral to the rectus muscle.

If clamping of the distal aorta was unsafe or unsound, an open distal anastomosis was performed first, and distal perfusion was restored after crossclamping of the graft. For the visceral segment, a beveled anastomosis was frequently used. If the visceral segment required circumferential replacement, individual catheters were directed into the celiac and superior mesenteric arteries and cold blood (mixture of 4 parts blood/1 part saline) was perfused for approximately 5 minutes every 20 minutes before the
artery was directly anastomosed to the graft or an intervening trifurcated graft (8–12 mm Dacron). A total of 23 patients (50%) in the DHCA group underwent reimplantation of at least 1 visceral vessel.

Motor Evoked Potential Monitoring

After induction, volatile anesthetics and muscle relaxants were discontinued, and narcotic anesthesia was substituted. MEPs were elicited and recorded as previously described in detail. A decrease of 50% in amplitude of the leg MEPs in the presence of stable hand MEPs was considered to reflect a lower body ischemic event. MEP monitoring was performed on 47 patients (61%) in the DHCA group. MEPs usually disappear when the core body temperature reaches 25°C during cooling, but are useful earlier in the procedure for assessing spinal cord integrity during ligation of the intercostal (segmental) arteries. In general, once the bladder temperature reaches 30°C or greater during rewarming, MEP signals begin to be detected again and may help assess the integrity of the spinal cord before the patient awakens from anesthesia.

Somatosensory Evoked Potential Monitoring

SSEPs were elicited by stimulation of the left and right posterior tibial nerves as previously described. Ischemic spinal cord dysfunction was defined as a decrease in SEP amplitude of more than 50%.

Cerebrospinal Fluid Drainage

In general, cerebrospinal fluid (CSF) drainage via a CSF catheter was used liberally. Approximately 80% of patients had a catheter placed. However, patients with infections, emergency surgery, dissections, previous lumbar spinal surgery, or hemodynamic instability did not routinely receive CSF drainage. SSEPs were elicited by stimulation of the left and right posterior tibial arteries at the top of the graphs represent the DIT of individual patients with no RAO. The circles at the bottom of the graphs represent the DIT of individual patients with RAO. RAO, Reversible adverse outcome; DIT, distal ischemic time; DHCA, deep hypothermic circulatory arrest.

Postoperative Management

The SSEPs were monitored until the patient awakened. Thereafter, hourly brief neurologic examinations were performed for 72 hours, and methylprednisolone was used for 72 hours (1000 mg, day 0; 375 mg, day 1; 250 mg, day 2). High normal blood pressures were maintained, aiming for a mean aortic pressure of 90 mm Hg. In a few patients, the pressure in the spinal cord collateral circulation was measured directly by means of a catheter in an intercostal artery. Patients were kept intubated for at least the first 24 hours.

Statistical Methods

Data were entered into Excel spreadsheets (Microsoft Corp, Redmond, Wash) and transferred to a SAS file (SAS Institute, Inc, Cary, NC) for data description and analysis. Patient and disease characteristics are described as percents, medians (range), or means (standard deviation). The 2 major categories of outcomes assessed were RAO (postoperative acute renal failure, liver failure, or temporary hemodialysis) and PAO (postoperative permanent hemodialysis, paraplegia, or mortality). For comparisons between DHCA and non-DHCA groups, chi-square or Fisher exact tests were used for categoric variables, and Student t tests were used for numeric variables, and Student t tests were used for age and body mass index. Figure 1 was generated using the smoothing technique, which involves local least-squares fitting of the data with a quadratic polynomial function.

A propensity score–matched analysis was undertaken to remove the unbalanced preoperative characteristics between the entire DHCA and non-DHCA groups. To maximize the overlapping of the 2 groups, we limited our selection of subjects to those who had DIT more than 10 minutes and less than 70 minutes. These bounds were chosen because they were close to the minimal DIT for the patients in the DHCA group (17 minutes) and the maximal DIT for the patients in the non-DHCA group (65 minutes) within the 80-minute range. A logistic regression was performed to predict the probability (ie, propensity score) of receiving DHCA using all of the preoperative characteristics listed in Table 1. Then we matched the non-DHCA subjects to the DHCA subjects according to the shortest distance of the predicted probability (propensity scores), using the sampling with replacement technique (ie, a subject can be matched more than once). This resulted in 45 successful matched pairs, as evidenced by Table 2.

Then, a stepwise logistic regression analysis was performed to identify significant predictors of RAO. The covariates considered in this model included propensity score, intraoperative variables (bladder temperature and DIT), and whether the operation involved DHCA, TAAA or DTA, or a stage II elephant trunk procedure. Preoperative creatinine was not included in the final model because all patients (100%) who had a preoperative creatinine greater than 2.5 mg/dL subsequently had at least 1 RAO.

Stepwise logistic regression analyses were performed to identify significant predictors of development of at least 1 PAO, first using the entire sample and then the matched subset. The covariates considered in the initial model included age, body mass index, DIT, bladder temperature, history of smoking, Crawford status, presence of preoperative stroke, and whether the operation involved DHCA, TAAA or DTA, acute or chronic dissection, reoperation, and stage II elephant trunk procedure. For analysis of PAO, presence of RAO and preoperative creatinine greater than 2.5 mg/dL were also considered as predictor candidates. Findings were reported as odds ratios (ORs) and 95% confidence intervals (CIs) for the identified risk factors.

RESULTS

Summary for the Entire Cohort

The preoperative and intraoperative characteristics for the entire cohort are listed in Table 1. A total of 134 patients (56%) were male; the mean age was 62.6 ± 13.2 years.
The 2 patient groups were similar. Twenty-five patients (29.6%) had a preoperative creatinine greater than 2.5 mg/dL, 44 patients (18%) were active smokers, 107 patients (45%) had a history of smoking, and 39 patients (16%) had a history of chronic obstructive pulmonary disease.

Thirty-day mortality rate was 7.1% (17/240); 6.1% of patients in the non-DHCA group and 9.1% of patients in the DHCA group died (\(P = .43\)). Ten patients had strokes: 5 (3.1%) in the non-DHCA group and 5 (6.5%) in the DHCA group (\(P = .3\)). Postoperative outcomes for the entire cohort included a 1.3% (3/240) incidence of paraplegia.

Overall, 121 intra-abdominal RAOs developed in 98 patients; 0.9% (3/322) incidence of paraplegia.
patients (40.8%) and 26 PAOs developed in 24 patients (10%).

Propensity Analysis Results

A propensity score–matched analysis was undertaken to eliminate the unbalanced preoperative and intraoperative characteristics in the DHCA and non-DHCA groups. The preoperative and intraoperative characteristics for the subset analysis are listed in Table 2. Postoperative outcomes are shown in Table 3.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Non-DHCA (N = 45)</th>
<th>DHCA (N = 45)</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>60.9 ± 12.8</td>
<td>58.4 ± 14.5</td>
<td>.42</td>
</tr>
<tr>
<td>Body mass index</td>
<td>27.5 ± 5.5</td>
<td>28.1 ± 6.1</td>
<td>.62</td>
</tr>
<tr>
<td>Sex</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>29 (64%)</td>
<td>30 (67%)</td>
<td>.82</td>
</tr>
<tr>
<td>Female</td>
<td>16 (36%)</td>
<td>15 (33%)</td>
<td></td>
</tr>
<tr>
<td>Cause</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dissection total</td>
<td>21 (47%)</td>
<td>23 (51%)</td>
<td>.67</td>
</tr>
<tr>
<td>Acute</td>
<td>1 (2%)</td>
<td>2 (4%)</td>
<td>1.00</td>
</tr>
<tr>
<td>Chronic</td>
<td>20 (44%)</td>
<td>21 (47%)</td>
<td>.83</td>
</tr>
<tr>
<td>Rupture</td>
<td>7 (16%)</td>
<td>6 (13%)</td>
<td>.76</td>
</tr>
<tr>
<td>Reoperation</td>
<td>17 (38%)</td>
<td>13 (29%)</td>
<td>.37</td>
</tr>
<tr>
<td>Active smoker</td>
<td>6 (13%)</td>
<td>8 (18%)</td>
<td>.56</td>
</tr>
<tr>
<td>Smoking history</td>
<td>25 (56%)</td>
<td>26 (58%)</td>
<td>.83</td>
</tr>
<tr>
<td>History of COPD</td>
<td>10 (22%)</td>
<td>8 (9%)</td>
<td>.60</td>
</tr>
<tr>
<td>Previous stroke</td>
<td>4 (9%)</td>
<td>3 (7%)</td>
<td>.69</td>
</tr>
<tr>
<td>Renal failure</td>
<td>7 (16%)</td>
<td>4 (9%)</td>
<td>.33</td>
</tr>
<tr>
<td>Acuity</td>
<td></td>
<td></td>
<td>.44</td>
</tr>
<tr>
<td>Urgent/emergency</td>
<td>8 (18%)</td>
<td>11 (24%)</td>
<td></td>
</tr>
<tr>
<td>Elective</td>
<td>37 (82%)</td>
<td>34 (76%)</td>
<td></td>
</tr>
<tr>
<td>DT</td>
<td>10 (22%)</td>
<td>19 (42%)</td>
<td>.04</td>
</tr>
<tr>
<td>TAAA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>35 (78%)</td>
<td>26 (58%)</td>
<td>.04</td>
</tr>
<tr>
<td>Crawford type 1</td>
<td>16 (46%)</td>
<td>18 (69%)</td>
<td></td>
</tr>
<tr>
<td>Crawford type 2</td>
<td>7 (20%)</td>
<td>5 (19%)</td>
<td></td>
</tr>
<tr>
<td>Crawford type 3</td>
<td>6 (17%)</td>
<td>2 (8%)</td>
<td></td>
</tr>
<tr>
<td>Crawford type 4</td>
<td>6 (17%)</td>
<td>1 (4%)</td>
<td>.20</td>
</tr>
<tr>
<td>Stage 2 elephant trunk</td>
<td>17 (38%)</td>
<td>1 (2%)</td>
<td>&lt;.01</td>
</tr>
<tr>
<td>Bladder temperature</td>
<td>31.7 [20.9–34.9]</td>
<td>16.1 [12.2–21.7]</td>
<td>&lt;.01</td>
</tr>
<tr>
<td>Perfusion/ischemic times</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPB time</td>
<td>42 [0–228]</td>
<td>168 [105–361]</td>
<td>&lt;.01</td>
</tr>
<tr>
<td>DHCA time</td>
<td>—</td>
<td>29 [13–47]</td>
<td>—</td>
</tr>
<tr>
<td>DIT</td>
<td>22.0 [13.0–59.0]</td>
<td>53.0 [17.0–68]</td>
<td>&lt;.01</td>
</tr>
<tr>
<td>Transfusion requirements</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Packed RBCs</td>
<td>2 [0–8]</td>
<td>1 [0–10]</td>
<td>.21</td>
</tr>
<tr>
<td>FFP</td>
<td>0 [0–10]</td>
<td>0 [0–11]</td>
<td>.58</td>
</tr>
<tr>
<td>Platelets</td>
<td>1 [0–10]</td>
<td>2 [0–20]</td>
<td>.24</td>
</tr>
</tbody>
</table>

*P* value is for testing the difference between the non-DHCA and DHCA groups. COPD, Chronic obstructive pulmonary disease; RBC, red blood cell; FFP, fresh-frozen plasma; SD, standard deviation.

All patients (100%) in the matched dataset (and nearly every patient [96%] in the entire dataset) who had a preoperative creatinine greater than 2.5 mg/dL also had at least 1 RAO (not considered in the model). No significant differences in the rates of permanent hemodialysis, paraplegia, stroke, 30-day mortality, or PAOs were observed.

As DIT increased (10 min < DIT < 70 min), a significantly lower rate of RAO was seen with DHCA compared with mild hypothermia (Figure 1). In the logistic regression analysis, variables associated with a statistically significant
TABLE 3. Postoperative outcomes comparing deep hypothermic circulatory arrest with non–deep hypothermic circulatory arrest (stage II elephant trunk or other) surgical procedure within the propensity score–matched subset (10 min < distal ischemia time < 70 min)

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Others (N = 28)</th>
<th>Elefphant trunk (N = 17)</th>
<th>DHCA (N = 45)</th>
<th>P values*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acute renal failure</td>
<td>13 (46.4%)</td>
<td>3 (17.7%)</td>
<td>10 (22.2%)</td>
<td>.16/0.03</td>
</tr>
<tr>
<td>Reversible hemodialysis</td>
<td>2 (7.1%)</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
<td>.49/0.07</td>
</tr>
<tr>
<td>Liver failure</td>
<td>11 (39.3%)</td>
<td>3 (17.7%)</td>
<td>37 (17.8%)</td>
<td>.14/0.04</td>
</tr>
<tr>
<td>No. of patients with RAO</td>
<td>19 (67.9%)</td>
<td>4 (23.5%)</td>
<td>16 (35.6%)</td>
<td>.14/0.01</td>
</tr>
<tr>
<td>Permanent hemodialysis</td>
<td>1 (3.6%)</td>
<td>0 (0%)</td>
<td>1 (2.2%)</td>
<td>1.00/1.00</td>
</tr>
<tr>
<td>Paraplegia</td>
<td>0 (0%)</td>
<td>1 (5.9%)</td>
<td>0 (0%)</td>
<td>1.00/0.00</td>
</tr>
<tr>
<td>30-d mortality</td>
<td>2 (7.1%)</td>
<td>3 (17.7%)</td>
<td>4 (8.9%)</td>
<td>0.73/1.00</td>
</tr>
<tr>
<td>DTA</td>
<td>0 (0%)</td>
<td>2 (25%)</td>
<td>0 (0%)</td>
<td>.11/0.00</td>
</tr>
<tr>
<td>TAAA</td>
<td>2 (7.7%)</td>
<td>1 (14.3%)</td>
<td>4 (15.4%)</td>
<td>.45/0.67</td>
</tr>
<tr>
<td>No. of patients with PAO</td>
<td>2 (7.1%)</td>
<td>4 (23.5%)</td>
<td>5 (11.1%)</td>
<td>.75/0.70</td>
</tr>
<tr>
<td>Stroke</td>
<td>1 (2.3%)</td>
<td>1 (2.3%)</td>
<td>2 (4.4%)</td>
<td>1.00/1.00</td>
</tr>
</tbody>
</table>

*The first P value is for testing whether DHCA and non-DHCA (others + elephant trunk) are the same using either chi-square test or Fisher exact test as appropriate. The second P value is for testing whether the DHCA and others are the same. Comparisons between elephant trunk and DHCA were all nonsignificant (P > .01, and 0.08 for DTA 30-day mortality).

decrease in the odds of developing RAO included DHCA (OR, 0.32; CI, 0.12–0.85) and stage II elephant trunk procedure (OR, 0.22; CI, 0.06–0.79). Of note, the protective effects of DHCA and elephant trunk procedure seemed to be similar (P = .06 for testing equality of the 2 ORs).

In view of the significantly lower morbidity of a stage II elephant trunk procedure in this analysis, and the fact that these procedures essentially never require the use of DHCA, we focused our comparisons of the propensity-score matched DHCA group with those in the non-DHCA group who did not have an elephant trunk procedures (Table 3). There was a statistically significant decrease in rates of acute renal failure in the DHCA group (22.2%) compared with those without an elephant trunk in the non-DHCA group (46.4%) (P = .03), and the rate of reversible hemodialysis was also marginally higher in the non-DHCA group (P = .07). Likewise, there was a decreased rate of liver failure in the DHCA group (17.8%) compared with the non-DHCA subset without an elephant trunk (34.3%) (P = .04). The percentage of patients with any RAO in the non-DHCA subset without an elephant trunk was 67.9%, compared with only 35.6% in the DHCA group (P < .01).

Relationship of Reversible Adverse Outcomes to Permanent Adverse Outcomes

In the entire sample, the development of any form of RAO increased the probability of developing PAO (OR, 4.69; CI, 1.78–12.37). There was also a significant trend toward an increased risk of PAO with higher numbers of RAO. The probability of developing PAO is 4.3% with no RAO, 16.7% with 1 RAO, and 20.0% with 2 RAOs (trend test P < .01). Once having developed RAO, the stage II elephant trunk group had a significantly increased risk of developing PAO (4/4 = 100%), compared with the DHCA group (3/16 = 18.8%, P < .01) and with the non-DHCA group without a stage II elephant trunk procedure (2/19 = 10.5%, P < .01). No significant difference was found between the latter 2 groups (P = .49).

In the logistic regression analysis with stepwise selection procedure for the entire cohort, only RAO (OR, 3.06; CI, 1.06–8.81) and preoperative creatinine greater than 2.5 mg/dL (OR, 4.34; CI, 1.45–13.02) were associated with the development of PAO. In the propensity score–matched logistic regression analysis, RAO (OR, 14.10; CI, 1.70–117.02) and acute dissection (OR, 23.5; CI, 1.05–528.02) were significant predictors of PAO.

COMMENTS

Open surgical repair of DTA and TAAA is a tremendous undertaking, requiring an understanding of various perfusion techniques and adjuncts to protect visceral and neuronal tissues. Recent advances in operative technique, neurologic monitoring, and adjunct procedures have resulted in decreased rates of surgery-related morbidity and mortality especially at high-volume aortic centers. Although various operative strategies have been developed and implemented, the optimal technique still remains unknown.

DHCA has been used to treat proximal aortic aneurysms with acceptable neurologic and psychomotor outcomes.12,13 Applying this approach to DTA and TAAA obviates the need for proximal and sequential aortic clamping, maintains a bloodless field, and minimizes aortic mobilization. Profound hypothermia offers protection to various visceral organs by decreasing metabolic rate and oxygen debt. By extrapolating from our aortic arch surgery experience, we approach selective DTA and TAAA operations with certainty that profound hypothermia results in acceptable organ protection.

Our current study shows that rates of RAO are decreased in patients who have undergone a complex aortic operation...
using DHCA compared with matched patients undergoing operation with mild hypothermia and distal perfusion. Significantly lower rates of renal failure and liver failure were seen in the DHCA group, in accord with a recent retrospective review demonstrating the safety of DHCA in patients undergoing elective, open thoracic aortic surgery. Reducing postoperative renovisceral morbidities also is likely to decrease patient intensive care unit recovery time, length of hospital stay, and overall cost, as well as resulting in fewer PAOs. In this study, the patients who had renovisceral complications had an average length of stay of 21 ± 23 days compared with 13 ± 10 days (P = .024) in patients without complications.

Acher and Acher and Wynn recently published their results of surgical outcomes in 771 patients undergoing DTA or TAAA repair. The operative technique used included mild hypothermia (<34°C), CSF drainage, rapid renal cooling, and intercostal reimplantation. They reported a postoperative hemodialysis rate of 3.2%, spinal cord ischemic injury rate of 3.3%, and mortality rate of 3.1% to 17.8% depending on acuity. The outcomes in the DHCA group in our study compare favorably with these results, providing further evidence that DHCA is an alternative technique with demonstrable benefit in preventing ischemia-related complications.

Staged elephant trunk procedures are often implemented in complex aortic pathology involving the ascending aorta, aortic arch, and descending thoracic aorta. Using this 2-stage technique avoids the need to clamp the aorta proximal to the left subclavian artery, which decreases the risk of neurologic complications. The presence of an elephant trunk theoretically reduces the likelihood of distal embolization from aortic crossclamping and shortens the duration of both CPB and DIT. LeMaire and colleagues showed a 4% postoperative hemodialysis rate, a 3% paraplegia rate, and a 4% operative mortality rate in patients undergoing stage II elephant trunk procedures for distal aortic repair. In this study, we found that the use of a stage II elephant trunk procedure resulted in a statistically significant decrease in the risk of the development of RAO when compared with other DTA and TAAA cases. Clearly, staged procedures are an important tool to decrease the risk of adverse outcomes in specific patient populations.

In the propensity-matched subset, RAO developed in a significant minority (40%) of patients with mild hypothermia and minimal DIT (Figure 1), whereas the DHCA group with the shortest duration of ischemia had a 15% RAO rate (Figure 1). In addition, the propensity analysis demonstrated a significantly lower risk of renal or liver failure in patients in whom DHCA was used. Inadequate pressure during distal perfusion (documented in a few patients in whom pressures were directly measured in the spinal cord collateral circulation during operation) may result in suboptimal protection for the viscera in operations using mild hypothermia. But it seems that there is an inherent risk for visceral injury regardless of operative technique, probably from physiologic stress, borderline visceral dysfunction, and operative atheroembolic events. Unrecognized visceral artery obstruction or occlusion may cause compromised perfusion to the visceral organs during operations carried out under mild hypothermia and may occur postoperatively in all patients. These phenomena are more likely in patients with atherosclerotic aneurysms and complex chronic aortic dissections. Vasconstrictors used in the postoperative period to maintain high mean arterial pressures to augment spinal cord perfusion may also have deleterious effects on visceral organ perfusion.

Preventing RAO and PAO is paramount when performing open DTA/TAAA repairs. Our data underscore the relationship of RAO to PAO in patients undergoing surgery regardless of technique: as the number of RAO increases, so does the likelihood of PAO. Although the rates of PAO are relatively low in our study and comparable to other studies performed at high-volume centers, there is still a definite risk of permanent hemodialysis and paraplegia, as well as stroke and death. These findings further demonstrate the need to orchestrate operations to eliminate or minimize visceral ischemia, and document that one effective strategy is to use DHCA.

Both the DHCA and mild hypothermia groups had statistically similar rates of red blood cell and fresh-frozen plasma transfusions. Proponents of the non-DHCA approach have resisted the implementation of DHCA in routine practice, arguing that the increased CPB time required to cool patients results in increased blood product use. However, patient-specific, standardized protocols involving routine use of antifibrinolytics and minimization of CPB time in DHCA have shown improved hemostatic outcomes.

**CONCLUSIONS**

For surgical procedures involving open repair of DTA and TAAA, the use of DHCA is a safe technique and likely superior to use of distal perfusion and mild hypothermia in preventing postoperative renovisceral comorbidity. Although DHCA may increase the complexity of the operative technique, lower temperature reduces complications occurring as a consequence of visceral ischemia. In patients with extensive aortic aneurysms and complex aortic dissections, a staged approach using an elephant trunk also reduces the incidence of RAO.

**References**


APPENDIX 1

Of the original 262 consecutive patients who were reviewed, 22 were excluded from the main analysis; 16 were excluded because they were on preoperative hemodialysis, and the remaining 6 patients did not have a recorded bladder or esophageal temperature. In addition, 3 of the 6 patients had missing DIT. All 6 patients had a non-DHCA repair, and their aneurysms were classified as follows: 1 Crawford type 1, 1 Crawford type 2, 1 Crawford type 3, and 3 Crawford type 4. An RAO developed in 3 of the 6 patients with incomplete data (50%), but none died.

If we were to add the fragmentary data from the 22 patients and include patients who were on hemodialysis preoperatively, the conclusions would be essentially the same but some statistics would change: (1) In Table 1, the P value for gender would change from .05 to .07. (2) In Table 1, the P value for reoperation would change from .04 to .06. (3) In Table 2, the P value for DTA/TAAA operations would change from .08 to .05. (4) In Table 2, the P value for red blood cells would change from .06 to .05.