Visceral and spinal cord protection during thoracoabdominal aortic aneurysm repair: Clinical and laboratory update

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The best method to protect the visceral and spinal cord during extensive aortic replacement remains debatable. Numerous surgeons have appropriately argued for their preferences because of the excellent clinical outcomes at their respective institutions. However, a scientific explanation for the greater success of a specific technique compared with the others has rarely been apparent. Many investigators have attempted to explain why certain adjuncts to minimize the risk of spinal cord injury (SCI) during thoracoabdominal aortic aneurysm (TAA) repair have physiologic benefits. Laboratory studies have shed light on some aspects of spinal cord protection, including the dynamics of blood flow and the anatomy of the blood supply to the spinal cord. However, despite the lack of clear scientific evidence for some of the protection techniques, surgeons have continued to achieve improved clinical outcomes.

VISCERAL PROTECTION WITH DEEP HYPOTHERMIA

Deep hypothermic circulatory arrest (DHCA) has been successful in providing acceptable neurologic and end-organ protection when applied to the treatment of the proximal aorta and arch aneurysms.^{1,2} In many cases of aortic arch repairs, DHCA (15°C–18°C) has afforded protection of visceral function for intervals as long as 90 minutes of lower body arrest.^{3,4} Aneurysms of the distal aorta, which are not amenable to the placement of an aortic crossclamp, have also been managed with HCA. Kouchoukos⁵ have had great success with a single-stage approach to aortic arch and descending aortic aneurysms using HCA. On the basis of these clinical scenarios, HCA has been applied to the repair of complex TAA.

Proponents of HCA have used this technique to reduce tissue metabolism and oxygen consumption in preparation for a period of ischemia.² Applying HCA to TAA obviates

the need for proximal and sequential aortic clamping and minimizes aortic manipulation and embolization. Selective perfusion of the visceral arteries is not usually performed, because it is not required with HCA. In contrast, it is a necessary adjunct when mild hypothermia is used. In our daily practice, HCA is conducted by cannulating the femoral arteries unless significant aortic atheroma or thrombus is present. In such cases, we use the axillary artery. The patient is cooled to a bladder temperature of 15°C, with a minimum cooling period of 30 minutes. If all visceral arteries need reimplantation, we commonly suture the limbs of a trifurcated graft to a rim of aortic tissue surrounding the individual ostia. The main limb of the trifurcated graft is sutured to the main aortic graft as soon as possible to begin perfusion of the viscera. In cases of type I TAA, the distal anastomosis to the visceral segment of the abdominal aorta is beveled, eliminating the need for individual grafts.

One of first publications on the use of DHCA in the treatment of TAA was by Crawford and colleagues⁶ in 1987, followed by reports from others of excellent early clinical outcomes using this technique. Fehrenbacher and colleagues⁷ and Kulik and colleagues⁸ are major proponents of this approach to TAA, with published operative mortality ranging from 5% to 7.3%. In a small series of descending thoracic aorta and TAA, Okita and colleagues⁹ reported no in-hospital deaths in cases managed with DHCA. More specifically, Fehrenbacher and colleagues⁷ reported an incidence of renal complications of 5.0% and of visceral complications of 3.5%. Patients with chronic renal insufficiency (creatinine >3 mg/dL) had a net change in creatinine from baseline of less than 3% when DHCA was used.¹⁰ In type II to IV TAA cases, the range of dialysis-dependent renal failure was 1.8% to 3.1%. Other investigators reported that the need for postoperative dialysis has ranged as high as 6.9% to 11%.^{8,11}

We recently reviewed our experience with the early outcomes of 262 TAA repairs during a 7-year period comparing the results using mild hypothermia and DHCA.¹² A propensity score-matched analysis was performed on the data from 90 patients. We focused our analysis on reversible problems (ie, temporary dialysis, renal failure, liver dysfunction) and permanent adverse outcomes (ie, long-lasting dialysis, stroke, paraplegia, and death). As the distal ischemia time—which includes the DHCA time and the time needed to re-establish lower body perfusion—increases, a significantly lower rate of reversible adverse outcomes (RAOs) occurs with DHCA than with mild hypothermia. The baseline probability of developing an

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Abbreviations and Acronyms

CNP	= collateral network perfusion pressure
DHCA	= deep hypothermic circulatory arrest
HCA	= hypothermic circulatory arrest
RAOs	= reversible adverse outcomes
SA	= segmental artery
SCI	= spinal cord injury
TAA	= thoracoabdominal aortic aneurysm

RAO was lower with DHCA (Figure 1). Both DHCA and stage II elephant trunk procedures were found on logistic regression analysis to be associated with statistically significantly lower odds of developing RAO. Patients operated on with mild hypothermia who did not have a stage II procedure had significantly greater rates of acute renal failure and liver failure than those operated on with DHCA. We have concluded that DHCA is a protective strategy that significantly reduces the incidence of renovisceral morbidity.

SPINAL CORD PROTECTION: CLINICAL AND LABORATORY OBSERVATIONS

The physiologic and anatomic aspects of spinal cord protection have been of enormous interest to our group. In any TAA repair, spinal cord protection remains a priority for the aortic surgeon. Although the understanding of spinal cord vascular anatomy and use of adjuncts and neuromonitoring varies among surgeons, the overall incidence of SCI has decreased at high-volume aortic centers. We have focused our research on building a comprehensive approach to SCI and advocating those measures that can be applied widely and seem to result in the best clinical outcomes.

COLLATERAL NETWORK CONCEPT

To minimize the risk of SCI during TAA repair, we have undertaken several studies to evaluate the anatomy, physiology, and varied histologic patterns of SCI. Our early studies defined the importance of extrasegmental vessels such as the subclavian and hypogastric arteries in safeguarding the spinal cord after extensive sacrifice of intercostal and lumbar (segmental) arteries.¹³ When either or both hypogastric or subclavian arteries are ligated, a significantly smaller number of segmental arteries (SAs) can be sacrificed without a loss of motor-evoked potential signaling than when these major arteries (hypogastric or subclavian arteries) remain patent.¹⁴ This set of experiments provided the first look into the elaborate and possibly redundant blood supply of the spinal cord. Our blood flow studies revealed that hypothermia reduces the metabolic requirements of the spinal cord and that a period of vulnerability to spinal cord ischemia exists for several hours after

extensive SA sacrifice.¹⁵ Blood flow to the paraspinous muscles is sevenfold greater than to the spinal cord. A surprising result, but one that correlated with the findings of subsequent vascular casting studies.^{16,17} In addition, the spinal cord blood flow to T8-L2, seems from these studies, to be the area most vulnerable to ischemia. It is also the area with the greatest difference in histologic damage when pigs that are paraplegic after extensive SA sacrifice were compared with pigs that recovered hind limb function.

The clinical implications of these studies is that concern with measures that ensure a stable milieu for optimal spinal cord recovery after surgery is paramount, including extreme vigilance in the immediate postoperative period with regard to blood pressure, avoidance of steal, and slow rewarming. Subsequent studies have successfully determined the collateral network perfusion pressure (CNP) by measuring the stump pressure of either L1 in pigs or the SA located in the middle of the aortic resection in surgical patients.^{18,19} We learned that the CNP decreases from about 70% to about 25% of the mean arterial pressure when all SAs are sacrificed and decreases further during the subsequent 5 hours. The CNP does not begin to recover until 24 hours postoperatively and does not return to baseline until 72 to 120 hours postoperatively. In surgical patients, the CNP decreases during cardiopulmonary bypass and begins to increase after pulsatile perfusion has been re-established. From the limited experience with CNP monitoring, it seems reasonable to maintain low central venous and cerebrospinal fluid pressures and to provide an elevated mean arterial pressure to maximize the CNP.

MANIPULATION OF THE COLLATERAL NETWORK

Our clinical observation of patients who had undergone extensive aortic replacement in 2 stages revealed a remarkably low incidence of SCI.²⁰ In our animal model, we designed a 2-stage approach to extensive SA sacrifice using an open and endovascular strategy.²¹ The decline in CNP observed after either the first or second stage of a 2-stage protocol was significantly less than after a 1-stage approach. None of the pigs in the 2-stage group manifested clinically detectable SCI, although histologically, a degree of tissue damage was seen. These studies suggest that collateral network remodeling and/or angiogenesis occur between the 2 stages, reducing the vulnerability of the spinal cord to ischemia.

ANATOMY OF THE COLLATERAL NETWORK

Our laboratory studies and clinical experience with extensive sacrifice of the SAs have given us clues concerning the potential expansiveness of the collateral network. Perfusion of the porcine model with a low viscosity acrylic resin revealed an extensively interconnected paraspinous muscle and intraspinal vascular network^{16,17} (Figure 2).

FIGURE 1. Probability of reversible adverse outcome with increasing distal ischemia time (*DIT*) in propensity score-matched subset plotted for non-deep hypothermic circulatory arrest (*DHCA*) compared with *DHCA*.

FIGURE 2. Anatomy of collateral network: A, sagittal and B, dorsal view. Macroscopic appearance of casts of pair of dorsal segmental vessels at L1. Dorsal process is removed. *X* designates paraspinous muscular vasculature providing extensive longitudinal arterioarteriolar connections; *triangle* indicates iliopsoas muscle.

Collateralization between the paraspinous muscle and intraspinal vascular networks dwarfs the role of the individual SAs and supports the premise that extensive SA sacrifice is possible owing to the resiliency of the network. In clinical practice, we have routinely maintained a high mean arterial pressure postoperatively to augment blood flow through this vascular network.

CONCLUSIONS

We remain enthusiastic about the beneficial effects of hypothermia on visceral and neuronal protection. Clinical data from multiple institutions support the use of *DCHA* for reno-visceral protection during complex aortic reconstruction. The results from our retrospective study suggest that *DHCA* reduces the likelihood of RAOs when a prolonged duration of distal ischemia is expected. Identifying patients who will benefit from *HCA* or from an elephant trunk procedure to decrease the interval of distal ischemia during the stage 2 procedure will continue to reduce the morbidity and mortality associated with open TAA repair.

SCI remains a dreaded complication after open or endovascular repair of TAAs. We are encouraged by our initial experimental studies, which have focused our attention on methods of manipulating the collateral network to eliminate the risk of paraplegia. The 2-stage approach, when feasible clinically, is promising. At present, however, this approach is limited by the morbidity associated with 2 open procedures and the limitations of current stent technology.

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