J CARDIOVASC SURG 2007;48:103-8

Cooling catheter for spinal cord preservation in thoracic aortic surgery

R. M. A. MOOMIAIE [1], J. RANSDEN [2], J. STEIN [2], J. STRUGAR [3], Q. B. ZHU [4], J. H. KIM [5], J. A. ELEFTERIADES [1]

[1]Section of Cardiothoracic Surgery
Yale University School of Medicine, New Haven, CT, USA
[2]Synectic Engineering, Inc., Milford, CT, USA
[3]Department of Neurosurgery
Yale University School of Medicine, New Haven, CT, USA
[4]Department of Anesthesia
Yale University School of Medicine, New Haven, CT, USA
[5]Department of Pathology (Neuropathology)
Yale University School of Medicine, New Haven, CT, USA

Aim. **Despite advances in spinal cord protection, paraplegia continues to be a serious complication of descending and thoracoabdominal aortic operations. We devised and tested a novel, self-contained catheter designed to cool the spinal cord topically after being threaded into the spinal column.**

Methods. **A cooling catheter for this purpose was specifically designed and produced. The catheter has two lumina, one for ingress and one for egress of fluid. The system is self-contained, so that the fluid does not communicate in any way with the spinal fluid. A console device circulates cold fluid through the catheter. The catheter was tested in 5 adult sheep, with direct monitoring of core body temperature and spinal cord temperature in both active cooling and passive re-warming cycles.**

Results. **In testing in 4 sheep (five attempted implants, with one failure), the catheter worked without problem, producing effective cooling of the spinal cord, from a mean temperature of 36.8 ºC (core temperature) to 30.5 ºC (spinal temperature) ($P<0.0001$). In no case did post-mortem examination or histology reveal any evidence of damage to the spinal cord from hypothermia. Temperature rose toward body temperature after cessation of active cooling.**

Conclusion. **Effective topical cooling of the spinal cord can be achieved via a specially designed, self-contained cooling catheter placed into the intra-thecal space. This catheter holds promise for spinal cord protection in aortic surgery. Also, this catheter may be useful as well in mitigating injury to the spinal cord in cases of traumatic spinal column injury.**

KEY WORDS: Aorta - Spinal cord - Paraplegia - Hypothermia.

Paraplegia has been a serious and recalcitrant problem since the advent of direct thoracic surgery some 40 years ago. Paraplegia continues to devastate the lives of certain patients undergoing surgery for thoracic aortic aneurysm; in cases of postoperative paraplegia, mortality is high and, even in survivors, quality of life is dramatically impaired.

We report here the initial laboratory experience with a novel catheter that permits direct topical cooling of the spinal cord without need for systemic hypothermia or fluid instillation into the intra-thecal space. The catheter is self-contained, is designed for percutaneous placement, and requires no maintenance during operation. This catheter is intended to reduce incidence and/or severity of paraplegia in aortic surgery, via topical hypothermia in the spinal canal. The present experiment explores the effectiveness of this cooling catheter in decreasing the temperature of the spinal cord in animals at systemic normothermia.

Materials and methods

Catheter

A catheter designed specifically for this purpose was developed according to our design characteristics by Synectic, Inc., Milford, CT (Figure 1). The catheter

Received on October 4, 2006.
Accepted for publication on July 22, 2006.

Address reprint requests to: J. A. Elefteriades, MD, 121 FMB, 333 Cedar St., New Haven, CT 06510, USA. E-mail: john.elefteriades@yale.edu

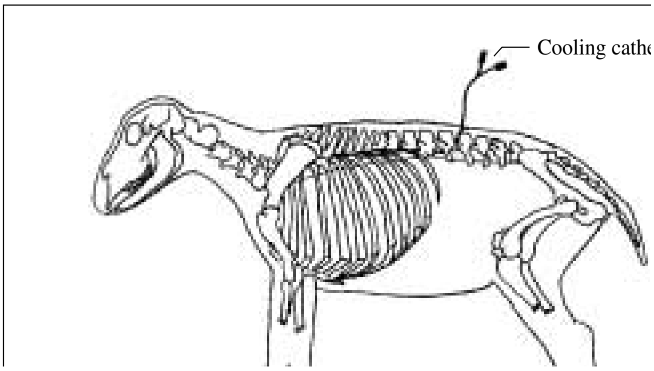

Figure 1.—Cooling catheter.

was designed to be the same caliber as what we currently use clinically for spinal drainage in adult humans. The catheter is a 5 F polyurethane device with two lumina that communicate through a fluid path at the tip. The catheter is soft and atraumatic, like the catheters currently in use for draining spinal fluid from the spinal canal. Saline from a cold bath is circulated by a suction device attached to the outflow limb. The catheter is placed so as to lie inside the intra-thecal space, from the lumbar site of placement a high thoracic level (Figure 2). The cold saline recirculated through the catheter has a temperature of -6 °C.

Experimental model

The laboratory experiments described here were conducted in adult sheep (weight range 26 to 57 kg, mean 42). This model was chosen for two reasons. First, the size and weight approximated those of adult

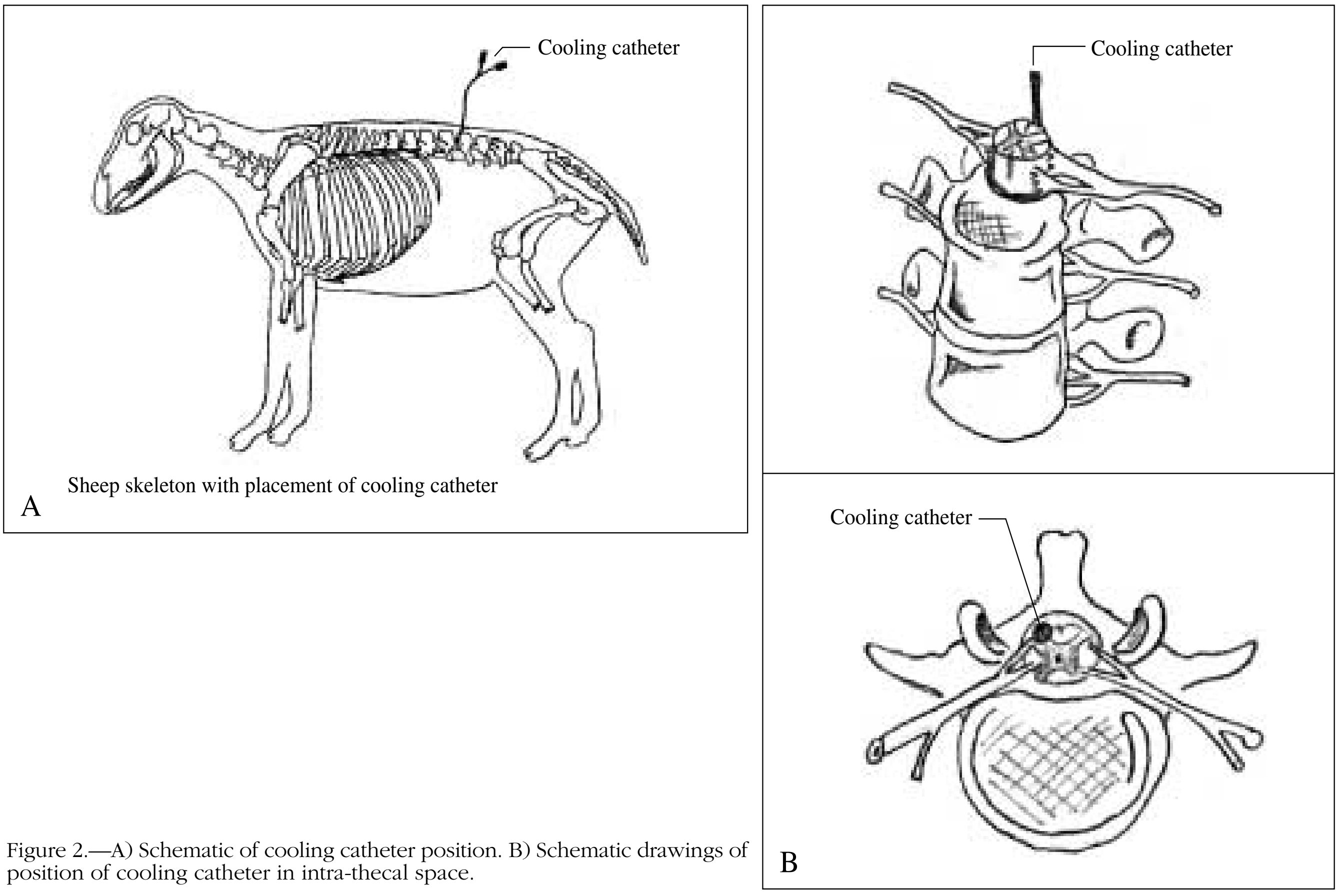

Figure 2.—A) Schematic of cooling catheter position. B) Schematic drawings of position of cooling catheter in intra-thecal space.

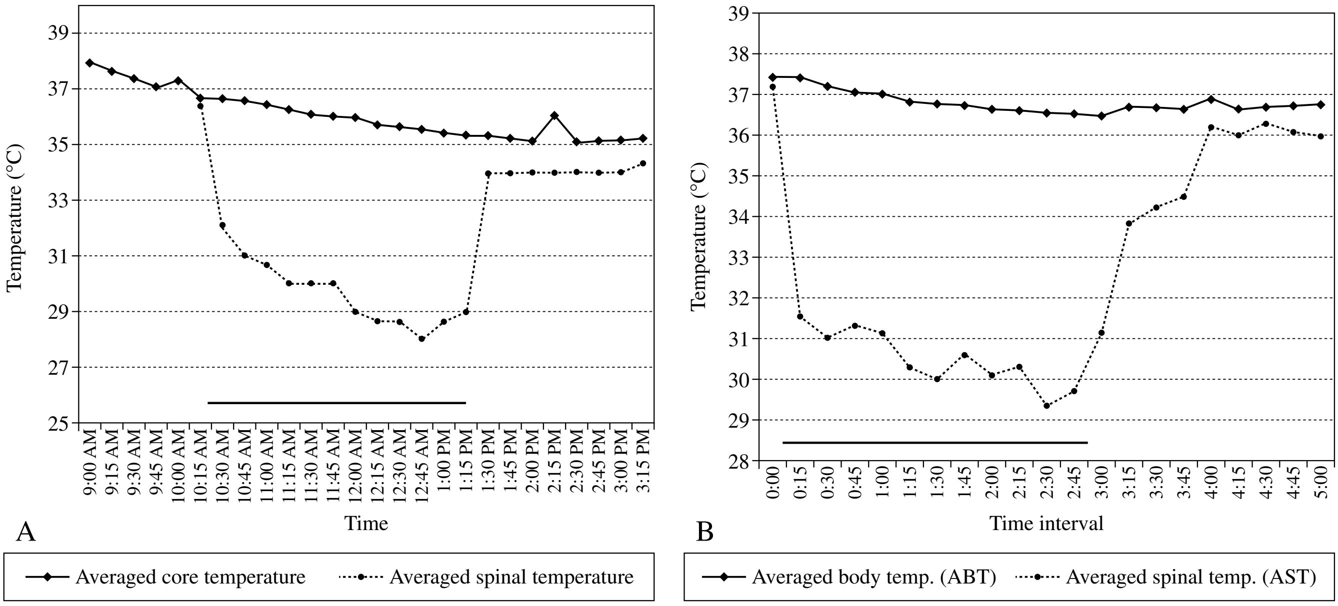

Figure 3.—A) Core temperatures (rectal) plotted against the averaged spinal temperatures (L4, T8, T4 levels) from one sheep experiment (best cooling example). Solid bar above x-axis represents cooling period. 3) Average temperatures (core and spinal) among all four animals. Solid line above x-axis shows cooling interval. Standard deviation of temperature differences was 0.15 °C.

human beings. Second, there was already a large experience, mainly in the obstetric literature, with intra-thecal catheter placement in this animal model.

Experimental procedure

All experiments were approved and monitored by the Yale University Animal Care and Use Committee. The animals were sedated with acepromazine 0.5 mg/kg intramuscular, valium 0.5 mg/kg *i.v.* and ketamine 1-2 mg/kg and intubated. The animals were maintained on spontaneous ventilation by isoflurane 1-2% in 100% oxygen for anesthesia, with pulse oximetry monitoring. The catheter was placed via laminectomy at the L5 level and threaded up to the level of the high thoracic vertebrae by direct length measurement. (Laminectomy is the standard procedure in sheep to ensure proper placement of intrathecal catheters; our system is designed to be fully suitable for standard percutaneous placement in humans). Needle-style temperature probes (Cooper-Atkins, Middlefield CT) were placed into the spinal cord itself at the L4, T8, and T4 levels by direct puncture of the spinal column through the intervertebral midline spaces. The tip of each temperature probe was positioned by feel to be lodged directly in the spinal cord substance. While maintaining normothermia of the animal, cooling of the spinal canal was begun by activating the spinal cooling catheter. Cooling was continued for 3 hours. The cooling catheter was then turned off and the systemic and cord temperatures followed for another 2 hours. The animals were euthanized at the completion of the experiment with Sodium Pentobarb 150 mg/kg i.v. A total of 5 experiments were performed. The spinal columns were opened and the spinal cords harvested for gross and histological analysis at postmortem examination after completion of the experiments.

Statistical analysis

The mean temperatures were compared by t-test (www.statcrunch.com), with $P<0.05$ considered significant.

Results

Technical performance

The catheter was able to be placed effectively in 4 of the 5 experiments. In one experiment, the catheter

TABLE I.—*Experimental results.*

Sheep experiment	Average body temperature (°C)	Average spinal temperature (°C)	N (ABT, AST)	Nadir spinal temperature (°C)	P-value (ABT *vs* AST)
Sheep 1	35.9	29.9	13	28	
Sheep 2	37.3	32.2	15	31	
Sheep 3	37.4	29.4	11	29	
Sheep 5	36.4	30.4	12	29	
Mean values	36.8	30.5	12.75	29.2	<0.0001

ABT= average body temperature (average of the rectal and esophageal temperatures per duration of the experiment); AST= average spinal temperature (average of the spinal temperatures at level L4, T8, and T4 per duration of the experiment); n=number of paired (ABT to AST) temperature readings for paired t test; NST= nadir spinal temperature; the single coldest spinal temperature reading noted during the experiment.

was felt to kink intrathecally (based on feel) and to advance suboptimally toward the thoracic level. The results of this experiment were omitted from analysis. Because of the blind approach in placing the spinal temperature monitors, it was noted that certain individual spinal probes read inconsistently with their neighbors; these probes were felt to be improperly positioned in the spinal cord tissue, and these measurements were omitted from the data analysis. The determination that an individual temperature probe was improperly positioned was made on the basis of marked reading discrepancy from all neighboring probes, supplemented by post-mortem examination of the spinal cord for absence of a puncture mark corresponding to the errant probe. The 4 experiments proceeded well for the duration of the 5 hour procedure, without other technical problems or incidents. The catheter and integral cooling circulation system functioned without problem in the four experiments.

Effectiveness of cooling

In all 5 experiments, the animals remained relatively normothermic, while the spinal cords cooled effectively. Figure 3A presents a representative temperature plot from one experiment. It can be seen that effective cooling of the spinal cord was achieved and maintained. Figure 3B presents the mean temperatures from all four successful animal experiments.

In the 4 experiments, the spinal cord achieved a plateau temperature of 30.5 ºC after 45 minutes, despite maintenance of a systemic temperature of 36.8 °C (Table I). The spinal cord hypothermia was successfully maintained until the conclusion of the 3-hour cooling phase. The spinal cord temperature rose continuously after cessation of cooling. The best cooling (animal 1) achieved a nadir cord temperature of 28 °C and the worst cooling (animal 2) achieved a nadir cord temperature of 31 °C. The regional temperatures at different levels in the spinal cord demonstrated fairly uniform cooling of the entire cord, with maximum difference between sites averaging 1.92 °C.

Post-mortem *examination*

Cooling catheters for the four successful experiments were found to be properly positioned. Puncture holes in the spinal cord could be seen, confirming appropriate placement of the intra-cord temperature probes. There was no evidence of trauma from the hypothermia catheter seen grossly or histologically. Histological analysis using hematoxylin and eosin preparations were done on all *post-mortem* harvests of the spinal cord of the sheep at sections corresponding with spinal temperature probe locations. No morphological changes were observed due to the hypothermic effect of the the cooling catheter. Figure 4 represents one representative histologic section from a sheep, indicating preserved cellular architecture.

Discussion

In recent years, there is a general sense that surgical science is doing better in preventing paraplegia. Multiple advances have expanded the anti-paraplegia armamentarium.[1-3] Rediscovery of left atrial-to-femoral artery perfusion for descending and thoracoabdominal operations has permitted reliable perfusion of the lower body and spinal cord.[1] Collagen-impregnated

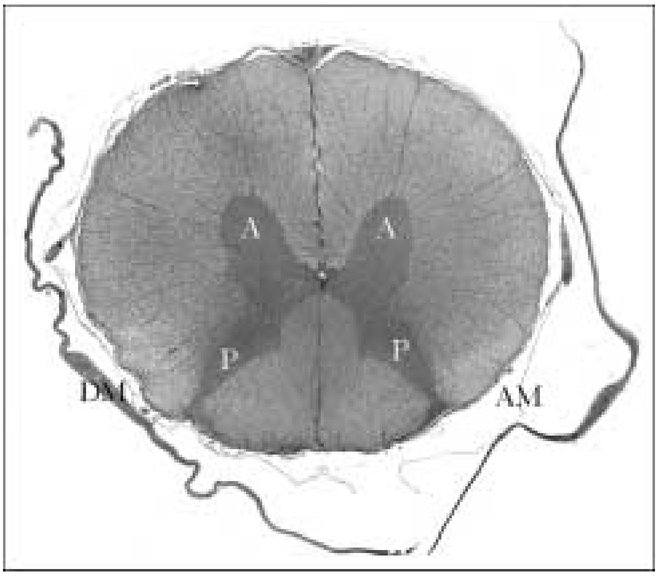

Figure 4.—A coronal section of the sheep spinal cord (Mag. X 20.3). A: anterior horn, P: posterior horn; AM: arachnoid membrane; DM: *dura mater*. Hematoxylin and Eosin stain. Histologically unremarkable. No pathology seen, except for pallor foci bilaterally in lateral columns, which may represent artifact.

grafts have improved hemostasis and inherent handling characteristics of available prostheses. Identification and re-implantation of spinal cord arteries have improved.[4-7] Spinal cord drainage, aimed at improving the perfusion gradient for the spinal cord, by minimizing external pressure on cord tissue, has been adopted almost universally.[8] Advent of effective anti-fibrinolytic agents has decreased perioperative blood loss and, consequently, led to improved hemodynamics. We have recognized the importance of maintaining proximal hypertension during the cross-clamp time. We have also recognized that sodium nitroprusside administration is contraindicated during surgery, because its administration can lead to increased intra-thecal pressure.[9] We have, as well, learned that by keeping blood pressure high after aortic replacement during the Intesive Care Unit (ICU) and step-down unit stays, we can prevent many cases of paraplegia. Also, we have recognized that early recognition and treatment of late postoperative paraplegia can often lead to restoration of spinal cord function; important measures include raising the blood pressure with inotropic medications and volume administration, optimization of hematocrit with blood transfusions, and reinstitution of spinal cord drainage.

Yet, paraplegia has not been reduced to zero incidence. This continues to be a major issue, both clinically and medico-legally.

The influence of hypothermia in protecting all tissues is well-known. The group of Cambria and colleagues in Boston have shown excellent results by continuously irrigating and draining the spinal canal with cold fluid, without any bypass perfusion adjuncts.[10] Despite good local results, this technique has not been generally adopted, because of concerns about the cumbersome nature of supplying and draining fluid and because of documented elevation in intrathecal pressure consequent upon fluid instillation. The experience of Kouchoukos *et al.*[11] with performance of descending and thoracoabdominal replacement under deep hypothermic arrest-with a near zero paraplegia rate-demonstrates vividly the powerful protective influence of hypothermia. Yet, most aortic surgeons do not utilize deep hypothermic arrest for descending and thoracoabdominal operations, out of concern for potential negative effects of deep hypothermia and prolonged perfusion in this setting.

These experiments that make up the present report confirm that this novel catheter for topical cooling of the spinal cord functions satisfactorily from a technical standpoint. Furthermore, the cooling catheter is able to produce very effective cooling of the spinal cord, to a mean spinal temperature of 30.5 °C. If one assumes an exponential decrement in metabolism (50% per 8 ºC),[3] this cooling can be expected to reduce the metabolic requirements of the spinal cord by about 33.3%. This degree of cooling is large enough to be of great clinical relevance. This degree of cooling was achieved in our experiments despite maintenance of systemic normothermia. A very recent study by Griepp *et al.* strongly supports the concept that hypothermia in the range achieved by the present cooling catheter may be of substantial clinical importance.[12] Their study found that moderate systemic hypothermia to 32 °C dramatically lengthened the tolerable ischemic interval for aortic cross-clamping in a porcine experimental model. The cooling catheter is able to achieve these cord temperatures even at systemic normothermia, and, furthermore, should be able to maintain these cord temperature reductions during the post-operative ICU recovery.

These were feasibility experiments designed to determine if such an apparatus as the cooling catheter was indeed able to produce direct topical cooling of the spinal cord in a large animal model. This was confirmed conclusively. Further study is needed, in animals or humans, to determine whether this topical cooling can translate to clinical benefit. We anticipate that it may prove effective to use the cooling catheter for the duration of descending and thoracoabdominal aortic surgery, and perhaps for one or two days post-operatively as well, as currently done in clinical practice with spinal drainage catheters. Because of the small space between the spines of the vertebral canal in the experimental animal, we chose to place the catheter via laminectomy. The size of the catheter is identical to that of the catheters we use routinely in human clinical practice to drain the spinal canal, thus suggesting strongly that the spinal cooling catheter can be placed percutaneously in human beings.

It is anticipated that cooling of the spinal canal via such a cooling catheter may also be of benefit in cases of spinal cord trauma, either traumatic or iatrogenic.

Conclusions

This experiment documents that a specially designed cooling catheter can effectively produce topical hypothermia in the spinal cord, despite systemic normothermia. This device and technique hold promise for decreasing the incidence and/or severity of paraplegia in aortic surgery.

References

1. Olivier HF Jr, Maher TD, Liebler GA, Park SB, Burkholder JA, Magovern GJ. Use of the BioMedicus centrifugal pump in traumatic tears of the thoracic aorta. Ann Thorac Surg 1984;38:586-91.
2. Hilgenberg AD. Spinal Cord Protection for Thoracic Aortic Surgery. In: Elefteriades JA ed. Diseases of the Aorta. Cardiology Clinics. Philadelphia: W.B. Saunders Company, 1999;17.p. 609-854.
3. Koullias GJ, Elefteriades JA. Neurological Complications in Cardiac Surgery. In: Little AG, Murray KD eds. Complications of Cardiothoracic Surgery: Prevention and Treatment. Elmsford, NY: Blackwell Publishing, 2004.p.405-35.
4. Kawaharada N, Morishita K, Hyodoh H, Fujisawa Y, Fukada J, Hachiro Y *et al.* Magnetic resonance angiographic localization of the artery of Adamkiewicz for spinal cord blood supply. Ann Thorac Surg 2004;78:846-51.
5. Elefteriades J, Weinreb J. Invited commentary. Ann Thorac Surg 2004;78:851-2.
6. Safi HJ, Miller CC 3rd, Carr C, Iliopoulos DC, Dorsay DA, Baldwin JC. Importance of intercostal artery reattachment during thoracoabdominal aortic aneurysm repair. J Vasc Surg 1998;27:58-68.
7. Elefteriades J, Coady M, Nikas D, Kopf GS, Gusberg RJ. “Cobrahead” graft for intercostals artery reimplantation during descending aortic replacement. Ann Thorac Surg 2000;69:1282-4.
8. Safi HJ, Hess KR, Randel M, Iliopoulos DC, Baldwin JC, Mootha RK et al: Cerebrospinal fluid drainage and distal aortic perfusion: Reducing neurologic complications in repair of thoracoabdominal aortic aneurysms types I and II. J Vasc Surg 1996;23:223-9.
9. Marini CP, Levinson J, Caliendo F, Nathan IM, Cohen JR. Control of proximal hypertension during aortic cross-clamping: effect on cerebrospinal fluid dynamics and spinal cord perfusion pressure. Semin Thorac Cardiovasc Surg 1998;10:51-6.
10. Cambria RP, Davison JK, Zannetti S, L’Italien G, Brewster DC, Gertler JP, et al: Clinical experience with epidural cooling for spinal cord protection during thoracic and thoracoabdominal aneurysm repair. J Vasc Surg 1997;25:234-43.
11. Kouchoukos NT, Daily BB, Rokkas CK, Murphy SF, Bauer S, Abboud N. Hypothermic bypass and circulatory arrest for operations on the descending thoracic and thoracoabdominal aorta. Ann Thorac Surg 1995;60:67-77.
12. Strauch JT, Lauten A, Spielvogel D, Rinke S, Zhang N, Weisz D, Bodian CA, Griepp RB. Mild hypothermia protects the spinal cord from ischemic injury in a chronic porcine model. Eur J Cardiothorac Surg 2004;25:708-15.