Spinal Cord Protection with Distal Perfusion for Thoracic and Thoracoabdominal Aortic Surgery

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Spinal cord protection is of extreme importance to avoid the catastrophic complication of paraplegia related to surgery for thoracic and thoracoabdominal aortic disease.[1,2,3] Spinal cord injury from surgically induced ischemia for aortic surgery has a variable risk of paraplegia. The incidence of spinal cord injury varies extensively-aneurysms of the proximal descending thoracic aorta and thoracoabdominal aorta 3% to 35%; to repair of traumatic rupture of the thoracic aorta performed with simple cross-clamping without distal perfusion, 25%; to repair of acute type B dissections of the thoracoabdominal aorta, as high as 35%.

The anatomical distribution of thoracic and thoracoabdominal aortic aneurysms has been classified by Crawford and colleagues[4] and shown in Figure 1 (reproduction from Safi et al[5]). Type I aneurysms involve most or all of the descending thoracic aorta plus the upper abdominal aorta. Type II aneurysms involve most or all of the descending thoracic aorta plus most or all the upper abdominal aorta. Type III aneurysms involve the distal descending thoracic aorta, plus most of the abdominal aorta. Type IV aneurysms, on the other hand, involve most of the abdominal aorta and none or very minimal of the descending thoracic aorta. The major risk of spinal cord injury occurs with surgery for type I to III aneurysms and not with type IV aneurysms.[4,6]

The variable anatomy and segmental derivation of the spinal cord circulation contributes to the risk of paraplegia and paraparesis. The blood supply of the spinal cord is derived from the segmental radicular arteries that supply the anterior spinal artery and the twin dorsal spinal arteries.[7] Intercostal arteries supply the middle thoracic segments while the major portion of spinal cord blood supply originates from the large, unpaired arteria radicularis magnus or great radicular artery of Adamkiewicz. This artery may arise anywhere from T8 to L3 but usually originates between T9 and T12. These vessels are usually involved in the aneurysm and, if ligated, reduce collateral circulation. During the performance of the aneurysm repair back bleeding from these vessels result in a steal phenomena.

The second most serious complication of surgery on the thoracic and thoracoabdominal aorta is renal failure and the requirement for dialysis. The third most significant complication is intraoperative and postoperative bleeding.

Controversy has existed over the past 10 to 15 years as to the optimal method for thoracic aneurysmectomy, repair of traumatic rupture of the thoracic aorta, and repair of complicated type B aortic dissection.[8-11] The use of adjuvants for perfusion of the distal aorta during aortic cross-clamping were advocated to prevent proximal hypertension and ischemic injury to

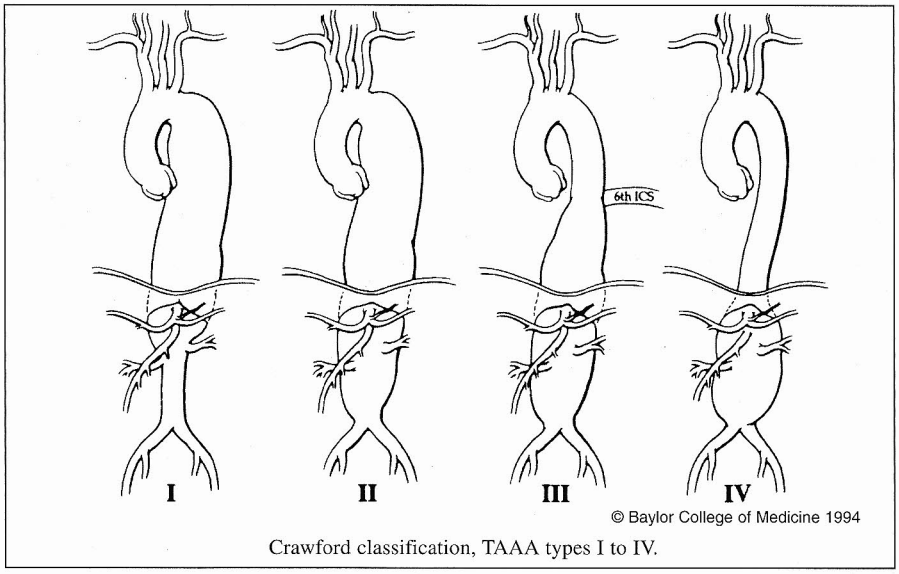

Figure 1. Crawford Classification (Reprinted from Safi et al. Neurologic deficit in patients at high risk with thoracoabdominal aortic aneurysms:the role of cerebral spinal fluid drainage and distal aortic perfusion. J Vasc Surg 1994;20(3):434-44).

the spinal cord and kidneys.[12] The temporary heparinized Gott shunt and partial cardiopulmonary bypass were advocated 15 and 20 years ago for distal perfusion during surgical management.[13] In 1973 Crawford and co-authors[14] concluded from personal experience and the literature that the simplified method of aortic cross-clamping alone avoided the complications of shunt management, reduced bleeding, and provided no additional risk to end-organ ischemia. The risk factors of spinal cord and renal ischemia subsequently received considerable attention and were ably reviewed by Livesay and co-authors[15] in 1985. These authors concluded that the risk factors of spinal cord injury were extent of aneurysms, emergency procedures and aortic cross-clamping greater than 30 minutes; while for renal failure, risk factors were advancing age and atherosclerosis. Kay and colleagues,[16] reporting in 1986 on aneurysms involving the distal aortic arch confirmed that paraplegia and transient renal failure where dependent upon the critical ischemic time of 30 minutes. The prevailing opinion of the early part of the past decade was that patient-related risk factors and lack of accurate, expeditious surgery were the predominant risk factors and that distal perfusion did not provide influential protection.

There has been extensive experimental evaluation and clinical documentation over the past decade on prevention of spinal cord injury and protection of renal function. The parameters that have been considered are technical, metabolic, pharmacological, and evaluative.

The monitoring of spinal cord function has received considerable attention.[17] In 1982 Laschinger and colleagues[18] reported on the utilization of sensory evoked potential monitoring (SEP) for detection of spinal cord ischemia during aortic cross-clamping. Sensory evoked potentials evaluate the posterior and lateral components of the spinal cord with intact peripheral nerve and cortical function. Dapunt and co-authors,[19] reporting in 1994, studied the pathogenesis of paraplegia in an elaborate canine model, demonstrating the effectiveness of sensory evoked potential monitoring in determining critical intercostal arteries for reattachment and prevention of steal phenomena from back-bleeding by serial intercostal ligation before aneurysm resection. Grossi et al.,[20] in 1985, showed that with venoarterial bypass in a canine model hypoxia increased spinal cord blood flow but spinal cord sensory function was only maintained with high flow rates and perfusion pressures. In 1988 Crawford and colleagues[14] compared patient groups with and without temporary distal aortic perfusion and somatosensory evoked potential monitoring and found no significant impact upon prevention of neurologic deficits. It can be concluded that the sensory evoked potential monitoring without other management modalities does not provide prevention of neurologic injury. Spinal cord monitoring by somatosensory evoked potentials has been criticized for failure to measure anterior (motor) spinal cord function. In a canine model Laschinger and co-investigators[21] identified that motor evoked potentials identify reversible ischemia that can be prevented by maintenance of adequate distal aortic perfusion.

The importance of spinal cord perfusion pressure (mean distal aortic pressure minus cerebrospinal fluid pressure) has been shown by Grubbs et al.[22] in a canine model of spinal cord ischemia. Drainage of cerebrospinal fluid increased spinal cord perfusion pressure while having no effect on distal aortic pressure but decreased the incidence of postoperative neurologic injury and somatosensory evoked potential loss. In the same year, 1988, McCullough and co-authors[24] demonstrated in a canine model that drainage of cerebrospinal fluid before aortic cross-clamping, increased perfusion pressure of the spinal cord and decreased the incidence of paraplegia. Kazama and co-investigators[23] identified in a canine model that removal of cerebrospinal fluid offers spinal cord protection only when cerebrospinal fluid pressure is abnormally elevated. Safi and colleagues,[5] in 1994, reported that neurologic deficit in patients with type I and II thoracoabdominal aortic aneurysm resection was significantly reduced by perioperative cerebral spinal fluid drainage and distal aortic perfusion. The neurologic deficit with and without cerebrospinal fluid drainage and distal aortic perfusion for type I aneurysms was 0% and 21%; for type II, 13% and 51%; aortic dissection, 12% and 28%; and with no dissection, 5% and 32%, respectively. The neurologic deficit for aortic cross-clamp times less than 45 minutes was 4% and 21%; and for times equal to or greater than 45 minutes, 14% and 48%, respectively. The patient populations compared came from different time periods.

The literature provides documentation of the effectiveness of both passive and active distal perfusion. Passive distal perfusion using the heparin-bonded Gott shunt has been extensively utilized by Verdant and colleagues[25,26] with excellent spinal cord protection. There is concern that complications can occur with placement of passive shunts and that distal flow cannot be effectively maintained.[27] In a series reported by Hamerlijnck et al.[28] two patients died of complications related to Gott shunt placement.

There has been considerable documentation of the utilization and effectiveness of active distal aortic perfusion (Figs. 2, 3). Cartier and colleagues[27] reported on the Mayo Clinic experience with repair of aneurysms of the descending thoracic

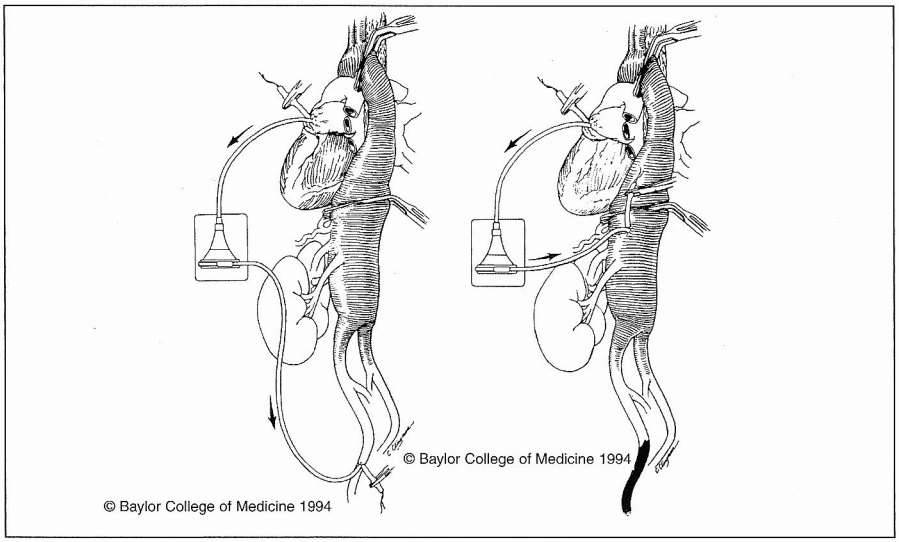

Figure 2. Diagramatic Technique Illustration of Use of Biomedicus Pump (Reprinted from Safi et al. Neurologic deficit in patients at high risk with thoracoabdominal aortic aneurysms:the role of cerebral spinal fluid drainage and distal aortic perfusion. J Vasc Surg 1994;20(3):434-44).

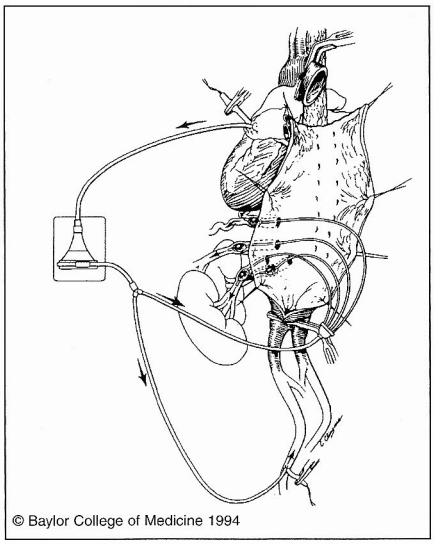

Figure 3. Diagramatic Technique Illustration of Use of Biomedicus Pump (Reprinted from Safi et al. Neurologic deficit in patients at high risk with thoracoabdominal aortic aneurysms:the role of cerebral spinal fluid drainage and distal aortic perfusion. J Vasc Surg 1994;20(3):434-44).

aorta. The study compared retrospectively distal active perfusion with the Biomedicus centrifugal pump, passive perfusion with the Gott shunt and simple aortic cross-clamping. The authors suggested the centrifugal pump may provide better protection than a passive shunt. The support of the distal circulation stabilizes hemodynamics and prevents renal ischemia. Walls et al.[29] evaluating a small patient series with left atrial-left ventricular shunt with roller and centrifugal pumps, Gott shunt and simple cross-clamp and recommended centrifugal pump without heparinization with the advantage of afterload reduction and stable distal perfusion. The work of Safi et al.[5] documented above also confirmed the effectiveness of heparinless distal perfusion with the Biomedicus centrifugal pump.

The combined utilization of non-heparinized Biomedicus pump for partial cardiopulmonary bypass and sensory evoked potential monitoring was reported in 1990 by de Mol and colleagues[30] in a series of 14 consecutive patients who underwent surgery for extensive thoracoabdominal aneurysms. These authors reported two cases of paraplegia and another that SEP monitoring assisted with identification and reattachment of a critical intercostal artery. These authors concluded that distal aortic perfusion with concomitant SEP monitoring offered an improvement of surgical strategy, and safer surgery. Ohmi and co-authors,[31] in 1995, recommended for surgical management of thoracoabdominal aortic aneurysms separate upper and lower body perfusion for control of intraoperative massive bleeding and cardiac arrest with major organs protected by hypothermia and perfusion. In the same year (1995), Shiiya et al.[32] documented the importance of combined reconstruction of segmental arteries and distal perfusion. In this study and another[33] both control of back bleeding and selective reconstruction contributed to reversal of loss of sensory evoked potentials. The determination of critical arteries did not completely prevent injury.

The surgical management of traumatic rupture of the thoracic aorta has also been controversial and evolutionary.[34-41] Traumatic injury of the aorta may occur intrapericardically, in the aortic arch or at distal sites but more commonly at the isthmus. Paraplegia has been documented to be as high as 25% with surgical repair.

The experience from the University of British Columbia over a twenty year period was reported in 1991 by Kodali and co-authors.[42] The use of partial cardiopulmonary bypass, either heparinized or non-heparinized, provided protection from paraplegia to a greater extent than simple aortic cross-clamping in a series of 116 patients (2.8% versus 28.5%). We recommended the use of non-heparinized bypass as the best surgical management to optimize spinal cord protection. Several authors have recommended partial cardiopulmonary bypass with oxygenation to provide no or minimal incidence of paraplegia.[43,12] It was recognized that distal perfusion decreased medullary ischemia and the risk of spinal cord ischemia but did not eliminate the problem. The use of partial heparinless bypass with a centrifugal pump, in a limited series by von Oppell et al.,[44] contributed to no hemorrhagic or paraplegia complications. There is always concern over the use of heparin with multiple injuries but Bouchart et al.[45] reported no ill effects with heparinization in 47 cases. In 1991, Kieny and Charpentier[46] identified that associated abdominal injuries are easily missed and for this reason exploratory laparotomy should be considered following every acute aortic repair. Pate and colleagues,[47] in 1995, documented that in their experience partial cardiopulmonary bypass with heparin was not contraindicated if other hemorrhage was controlled primarily. The chronology of operations in multiple trauma has been reviewed by Fasquel and co-authors[35] and the suggestion has been gastrointestinal, vascular, neurosurgical and orthopaedic.

A meta-analysis of mortality and risk of paraplegia for repair of traumatic aortic rupture was reported by von Oppel et al.[48,49] in 1994. The authors analyzed the results of 1492 patients, including those from the University of British Columbia.[42] Paraplegia was evident preoperatively in 2.6% of patients and 9.9% postoperatively. There were an additional 250 patients who died following hospitalization prior to surgery. Of the patients managed with simple aortic cross-clamping, the hospital mortality was 16%, with incidence of paraplegia, 19.2%; passive shunts, mortality 12.3% and paraplegia 11.1%; and active perfusion, paraplegia 2.3%. In this active group, the mortality using cardiopulmonary bypass with full heparinization was 18.2% and with heparinless

distal perfusion, 11.9%. The conclusion of the metaanalysis was a recommendation for heparinless partial cardiopulmonary bypass.

There have been other techniques documented for other complicated thoracoabdominal aortic aneurysms especially when related to chronic dissection. Segmental sequential reimplantation of intercostal arteries with active distal perfusion and cross-clamp progression distally has been advocated for adequate spinal cord protection.[50] Grabenwoger et al,[51] reporting in 1994, recommended profound hypothermia and circulatory arrest for complex reconstructions for thoracoabdominal aortic aneurysms. These authors were able to successfully reimplant patent lower intercostal and lumbar arteries (T3 to L5). The mortality in this complicated series was 21% (3 of 14) with no permanent neurologic deficit or renal or cardiac problem. In 1989 Caramutti and co-investigators[52] reported the use of deep hypothermia and circulatory arrest with total cardiopulmonary bypass via the femoral-femoral route as a viable choice for treatment of type B aortic dissection involving retrograde dissection to the aortic arch. An extended technique was presented by Yasuura et al,[53] in 1994, with hypothermic total body retrograde perfusion for complicated rupture or atheroembolism using retrograde superior vena caval, coronary sinus and inferior vena caval perfusion.

Pharmacological manipulation has been investigated and utilized for spinal cord protection. Sodium nitroprusside was initially utilized to control proximal hypertension with the simple aortic cross-clamping technique but was found to be deleterious because of alteration of spinal cord perfusion pressure.[54] Blood supply may also be maximized by dilatation of collateral blood flow utilizing either papaverine, prostacyclin or magnesium.[55-57] Svensson et al[57] studied intrathecal papaverine in 19 patients and indicated the method was of some merit. Simpson et al[55] showed, in a canine model, that intrathecal magnesium prevented spinal cord injury despite a markedly negative effect on spinal cord perfusion pressure.

Metabolic factors have been shown to also affect spinal cord integrity. There has been investigation on the avoidance of hyperglycemia including lactate level elevation which facilitated elevation of the metabolic rate of the spinal cord.[58] The use of profound hypothermia for difficult technical circumstances can be considered protective of spinal cord function.[59,60] There has been some experimental work in perfusion cooling of the intrathecal space providing hypothermia to the spinal cord.[61,62]

The techniques of prevention of spinal cord injury have also incorporated reduction of reperfusion injury. Laschinger et al[63] in 1984 evaluated the beneficial effects of corticosteroids. The concept of prevention of reperfusion injury of the spinal cord has incorporated oxygen free radical scavenging. Lipid perioxidation from oxygen free radical injury may be a serious mode of damage due to the high lipid content of the spinal cord. There has been experimental work evaluating the role of superoxide dismutase, allopurinol and deferoxamine. These modalities have been evaluated at the University of British Columbia by Qayumi and colleagues[64,65] demonstrating that the best protection in a canine model was with the combination of allopurinol for a three day period and deferoxamine for three or four hours prior to the procedure. In this experimental endeavour control animals, after thirty minutes of ischemia, were paraplegic while animals treated with allopurinol and deferoxamine were walking at 24 hours.

The utilization of distal non-heparinized perfusion using the Medtronic Biomedicus pump and Carmeda heparinized equipment has been evaluated for seven years at the University of British Columbia, the Vancouver Hospital and Health Sciences Centre. The first report was incorporated by Kodali et al,[42] in 1991, in an extensive study of traumatic rupture of the thoracic aorta. In 1994 Janusz[66] reported on 48 thoracoabdominal aortic aneurysm resections, 18 with simple cross-clamping and distal perfusion, with Gott shunt in six patients and heparinless left heart bypass with the Medtronic Biomedicus pump in 24 patients. There was no paraplegia or renal failure in the active perfusion group. In the simple cross-clamp group there were two cases of paraplegia but both patients experienced intraoperative cardiac arrest, one for a prolonged interval. It was the opinion at this time that distal heparinless perfusion may help reduce the risk of paraplegia and renal failure. The Vancouver Hospital experience was further documented by Janusz[67] in 1995 in an overall ten year total of 88 patients. The etiology of aortic lesions was trauma in 28 (23 acute and 5 chronic), degenerative in 36, complicated acute dissections in 10 and miscellaneous in 14 (mycotic, false aneurysm, chronic dissection, coarctation and thrombosis). The Biomedicus pump was used to facilitate distal perfusion in 56 patients. The mortality was 12% in 42 emergency operations and zero in 46 elective operations. There were three cases of paraparesis, all in cases of ruptured aneurysms-two managed with aortic cross-clamping and one with cardiopulmonary bypass. There were no cases of renal failure. Stroke occurred in two cases when the cross-clamp was placed between the left common carotid and left subclavian.

The previous documentation from the University of British Columbia on traumatic rupture of the thoracic aorta was the 20 year review of 1969 to 1989 at both Vancouver Hospital and St. Paul's Hospital.[42] The Vancouver Hospital experience between 1989 and 1995 has been 22 patients without a fatality. Twenty-one patients were managed with left heart bypass, of these 19 with non-heparinization and Biomedicus pump and 2 with heparinized cardiopulmonary bypass. There has been no cases of spinal cord injury or renal failure. The remaining case was hemorrhaging at commencement of surgery, had extensive extra aortic injuries and required ischemic time of 60 minutes resulting in paraplegia.

During the years 1994 and 1995 at Vancouver Hospital 12 cases of descending aortic aneurysm and 13 cases of thoracoabdominal aortic aneurysm were managed surgically (personal communication MT Janusz). In the descending aortic aneurysm series all were managed with non-heparinized distal perfusion with the Biomedicus pump with one case of spinal cord infarction and no renal failure. The mean ischemic time in the series was 50 minutes (range 28-81 minutes) and the ischemic time in the case of spinal injury was 55 minutes. The 13 cases of thoracoabdominal aneurysm resection were all managed with distal perfusion with the Biomedicus pump except one. There were three fatalities, 23%. The Biomedicus group was complicated by two deaths, one case of paraplegia and two cases of renal failure. The additional case was managed for ruptured aneurysm with simple aortic cross-clamping and died with complications of renal failure and paraplegia, the ischemic time was 68 minutes. The mean ischemic time for the thoracoabdominal series was 85 minutes (26-230 minutes). These series were performed with reimplantation of large intercostal and lumbar arteries and visceral arteries without sensory evoked potential monitoring or spinal fluid pressure monitoring.

MEDTRONIC BIOMEDICUS PUMP

The Medtronic Biomedicus pump is a centrifugal pump that operates on the principle of a constrained forced vortex. The pump promotes the vortex principle when fluid is put in circular motion. In a vortex there is an area of high pressure at the outside of the vortex and an area of low pressure in the centre of the vortex. The Biomedicus pump forces this vortex and imparts even more energy to the fluid by adding a series of three stacked rotator cones. (Figures 4,5). The magnet at the base of the cones attaches to the console magnet. The console turns the magnets, the cones spin, and the vortex is created. The smooth rotating surfaces of these cones provide more internal surface area and increase the energy imparted to the fluid.

The Biomedicus pump then constrains this forced vortex by fixing an outer housing over the nest of cones. The energy that goes into lifting the fluid is constrained and the pressure increases, causing the fluid to exit at the outlet (on the side of the pump) where the pressure is greatest and enter at the inlet (centre of the pump) where the pressure is the least. The constrained forced vortex principle of the Biomedicus pump makes it a constant energy pump. As the cones of the pump rotate, energy is imparted to the fluid in two forms-potential energy or pressure, and/or kinetic energy or flow.

The Biomedicus pump has been compared to impeller pumps and roller pumps. The Biomedicus pump is not likely to add macro air and holds micro air in the centre of the pump longer than the impeller pumps. The Biomedicus pump does not cause particles to be released from tubing. With the Biomedicus, flow changes gradually with slight pressure change. The pump tends to trap blood clots and avoid propulsion. The pump compensates for turbulence, avoids acute hemolysis and contributes to minimal postoperative hemolysis.

The perfusion technologies of the three classes of pumps differ. The roller pump operates by positive displacement as the rollers push the blood along, but the leading and trailing edges of the rollers create turbulence in the blood. With the impeller centrifugal pump the impeller blades push through the blood creating turbulence in areas of positive pressure (leading edge) and negative pressure (trailing edge). The Biomedicus centrifugal pump provides smooth, rotating cones which create viscous drag so the pumping action is smooth and gentle and the blood does its own pumping.

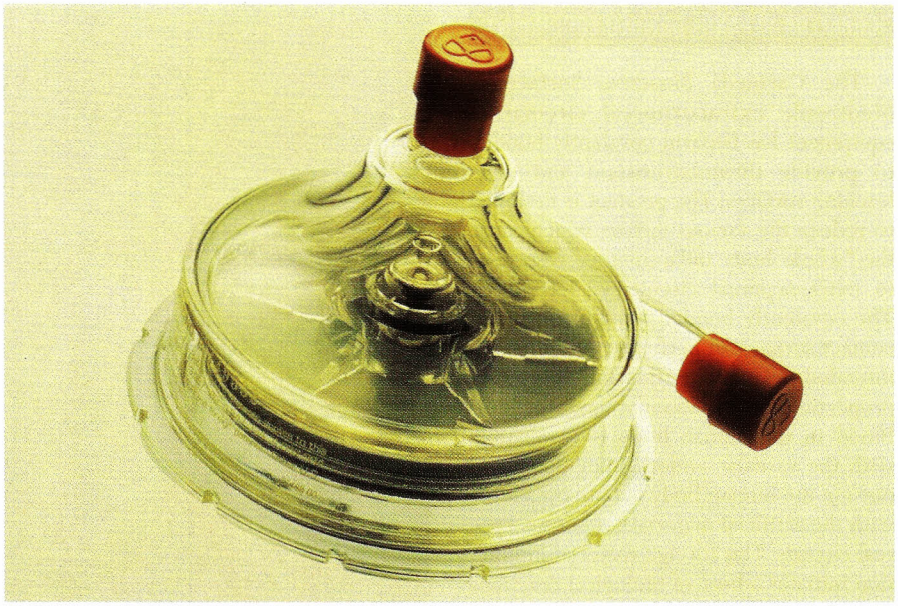

Figure 4. Biomedicus vortex pump

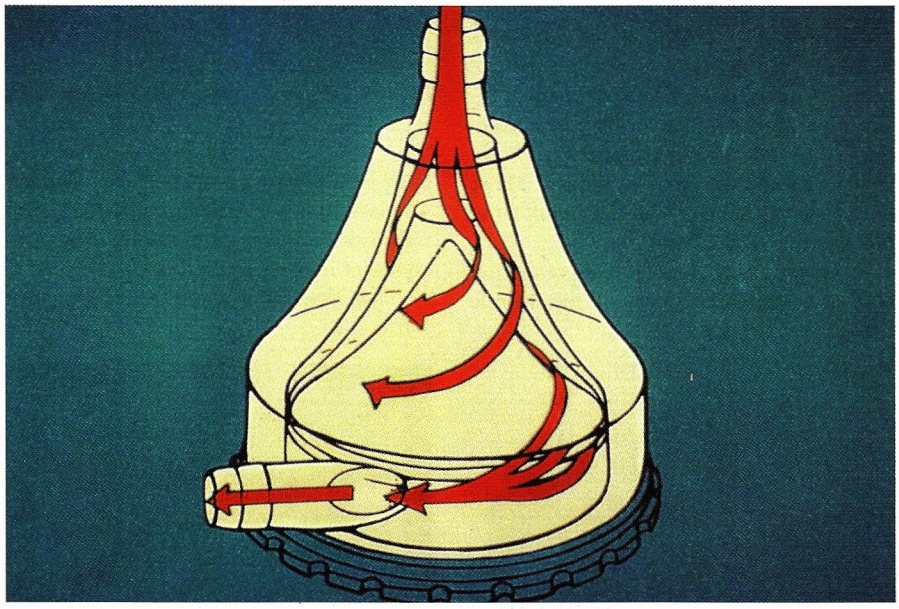

Figure 5. Vortex pump demonstrating the three stacked rotator cones

The Biomedicus pump controls use electromagnetic flow (EMF) measurement. With the 550 Bio-Console pump speed controller and TX50 Bio-Probe flow transducer, the natural conductivity of the blood is used to determine the actual flow rates.

The Biomedicus pump controls for complications-avoids over-pressurization, less risk of cavitation, less risk of gaseous embolism, no spallation and reduced risk of particle embolization, as well as less post-filter microbubble transmission compared to impeller or roller pumps.

The electromagnetic flow functions on the transmission of blood force perpendicular to the transducer electromagnet. The voltage produced by blood flow occurs when the magnetic field is at right angle to magnetic flow. The voltage produced is directly proportional to the velocity of flow. The resulting voltage sensed by the electrodes is directly proportional to the velocity of blood flow.

Figure 6 demonstrates the cannulation methodology for the Biomedicus pump as do figures 2 and 3. The components of the Medtronic Biomedicus pump are illustrated in figures 8 to 10.

CARMEDA HEPARIN BONDED EQUIPMENT

The Carmeda Bioactive Surface of Medtronic extracorporeal circulation equipment has heparin covalently bonded to provide thromboresistant and non-leaching surfaces. The product is designed to reduce the various factors which cause the "whole body inflammatory response" to extracorporeal circuitary[68-73] (Fig.11). The covalently bonded heparin on blood contact surfaces of perfusion equipment is intended to imitate the biocompatible properties of the vascular endothelium. Blood in the human body is compatible with the vascular endothelium but blood outside the human body is not compatible with the artificial materials of extracorporeal circuits. This foreign material interaction initiates a host of biological reactions involving defensive systems of the whole body, namely: coagulation, fibrinolytic, complement, kallikrein and kinin systems. These systems involve blood elements such as activation and consumption of platelets, activation of leukocytes and destruction of red blood cells. These reactions cause release of destructive enzymes, endotoxins and oxygen free radicals. These biological reactions are all normal defense mechanisms of the body.

It has long been evident that prevention of the deleterious effects of the "whole body inflammatory response" is beneficial. The lack of heparinization in patients with traumatic rupture of the aorta and concomitant injuries is also beneficial.

There have been three types of heparin bonding, namely ionic bonding, covalent bonding and grafting and end-point attachment of heparin. The tridodecylmethylammonium chloride (TDMAC)-heparin complexes is the ionic bonding technique

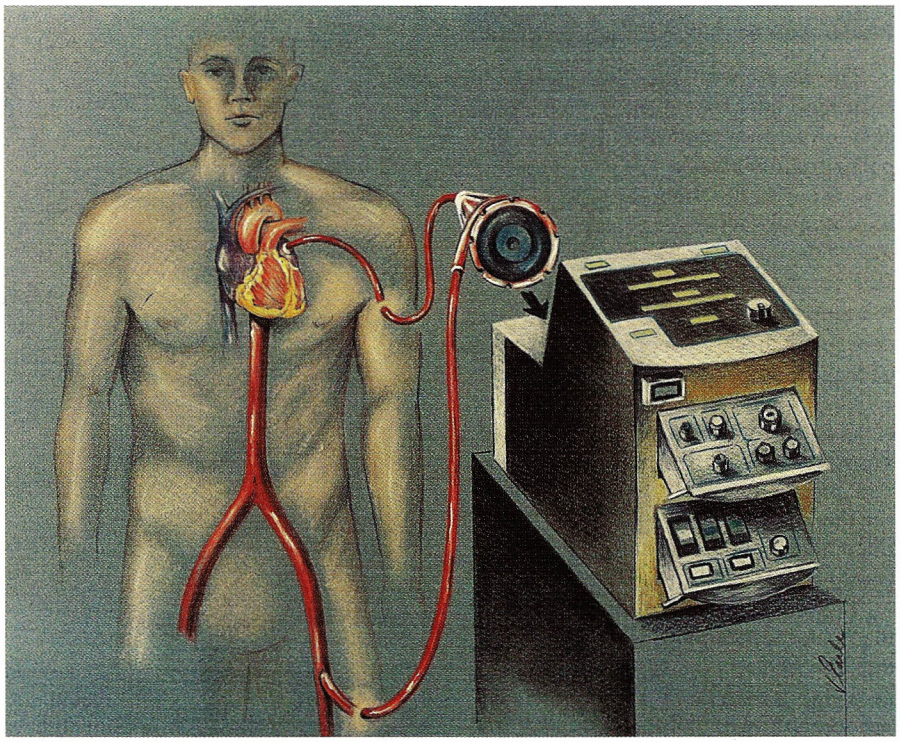

Figure 6. Diagramatic presentation of Biomedicus pump system in action.

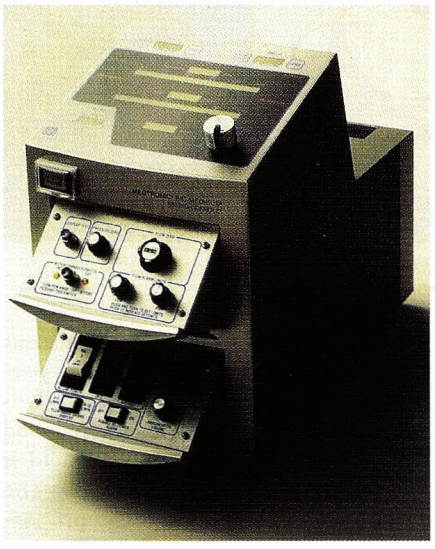

Figure 7. Presentation of regulatory components of the Biomedicus pump Ergonomically designed console with the display emphasizing flow, pressure and RPM values. A digital output connector will send flow, RPM, pressure measurements and alarm conditions to printer or computer at specified intervals. The system has a low RPM mechanical stop at 2000 PRM. To reduce below 2000 must press down on lever while turning RPM knob. The pump has an emergency handcrank, with illuminated display (1000-3250RPM).

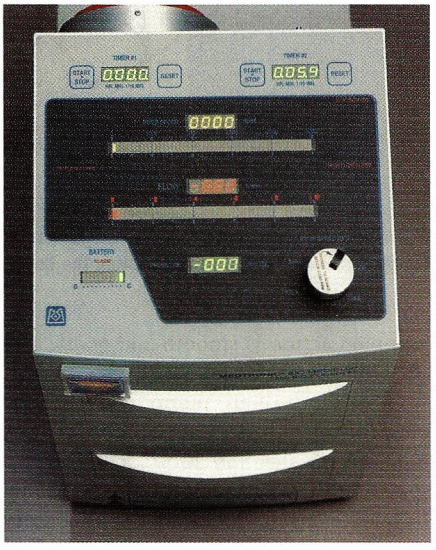

Figure 8. Area I Panel: Area I is used constantly during procedure. Operational functions of pump speed (RPM), displays for flow, displays for flow pressure and RPM, visual alarms for flow, AC power, and battery status and two timers. Flow speeds 0 to 4500 RPM.

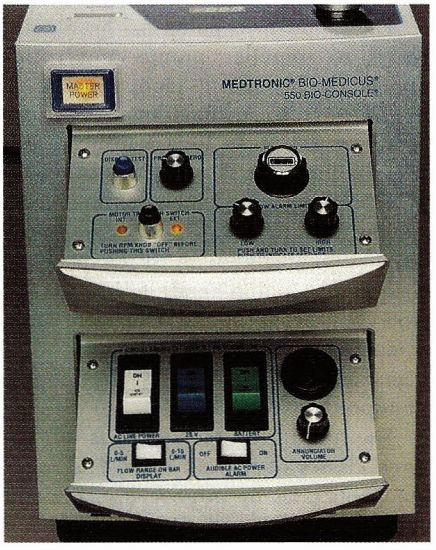

Figure 9. Area II Panel: Master switch activates AC power to console. Area II used to set the system and may be used during procedure. Area II panel is the first tilt-down drawer of console-adjustment knobs for zeroing flow and pressure transducers, switch to test displays of Area/Panel, adjustment knobs for setting alarms and switch for transferring to either internal or external motor.

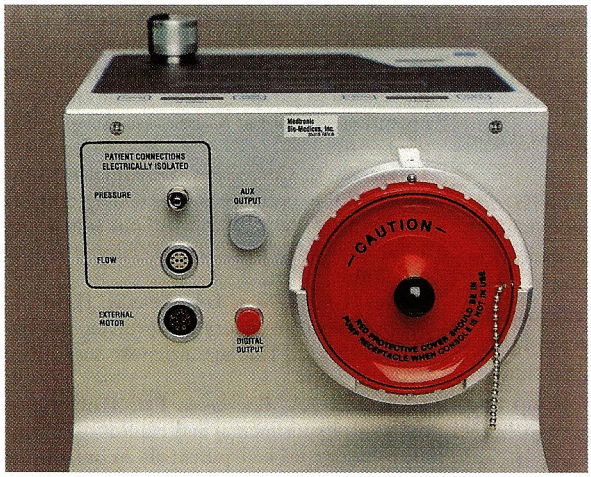

Figure 10a. Back of Console: Connectors for magnetic couple of centrifugal blood pump model BP 80 (adult) and model PB 50 (pediatric), pressure transducer connector, flow transducer connector, external motor connector, digital output connector, auxillary output connector, battery cord receptacle and battery receptacle and plug, fan for cooling inside of console and serial number plate.

Figure 10. Area III Panel: Area III may be used during procedure. Area III is contained in bottom of tilt-down drawer. Contains items for adjustment for three circuit breakers — switch to change to a 5 L/min to 10 L/min visual flow range, switch for audible sound for AC power off alarm and the alarm volume. Panel Area III can be closed during operation to protect from potential fluid damage.

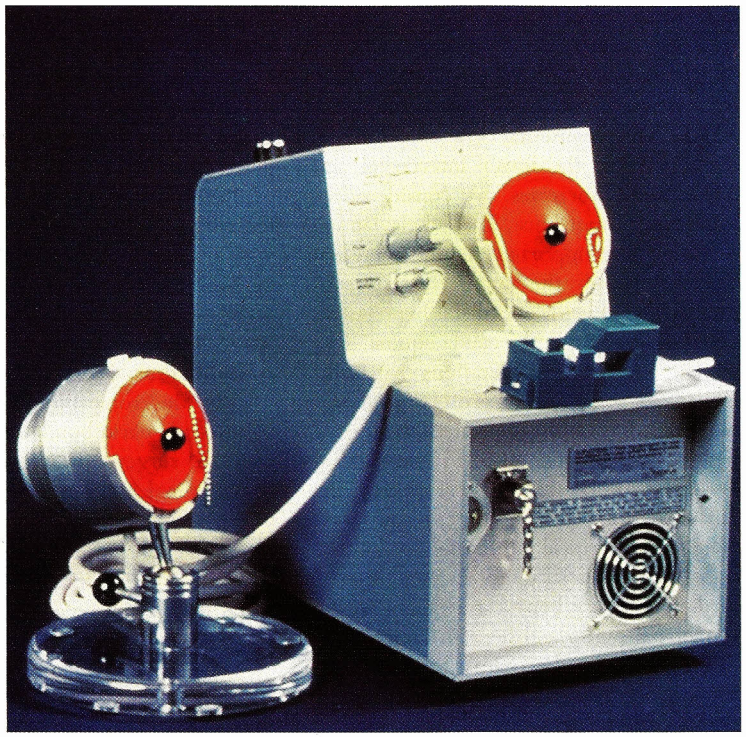

Figure 10b. Back of Console and Connections to Pump.

used in Gott shunts and Bentley Duraflo II heparin equipment. It is known that these surfaces leach when in contact with blood. With covalent bonding and grafting the orientation of heparin could not be controlled and the active antithrombin III binding site would not always be available. The end-point attachment of heparin in the Carmeda process mimics the orientation of heparin on the plasma membrane of natural endothelial cells.

The Carmeda end-point attached heparin allows binding to antithrombin III, the normal physiological inhibitor of the coagulation cascade.[74,75] The attachment of the activated coagulation factor to antithrombin III forms harmless inactive complexes which prevent thrombin from activated fibrinogen and eventually forming fibrin and organized thrombi. End-point attached heparin is felt to inhibit factor XII at the initiation of the coagulation cascade. The high affinity heparin binds factor XII and inhibits its conversion to activate factor XIIa. The inhibition of factor XII efficiently prevents thrombosis and also inhibits other defense systems. These properties help reduce the whole body inflammatory response. Carmeda end-point attached heparin binds antithrombin III and other factors and to provide active sites on heparin to bind appropriate factors in blood.

The Carmeda process was patented in 1983 by Larm and colleagues.[76] Heparin is covalently bonded to prevent release, prevent leaching and maintain reactive portion of the heparin structure.[77] The heparin coated Biomedicus pump and extracorporeal equipment affects the activation of coagulation, fibrinolysis, complement, kallikrein and kinin systems.[78,79] The utilization of this equipment has been shown to reduce bleeding, lower fibrinolysis, reduce hemolysis but not to affect platelet numbers or adhesion.[75] The Carmeda process improves biocompatibility by inhibiting C5a complement activation.[80]

Further documentation has confirmed that Carmeda heparin bonding preserves circulatory platelet numbers and aggregation properties and greatly inhibits release of platelet factor 4 and thromboxane B2 from platelets.[79,81] There is also evidence of less activation of granulocytes.[82] There is no requirement for protamine administration at the completion of extracorporeal support. There is general improvement with this technology regarding biocompatibility to perfusion circuits as well as thromboresistance.[83]

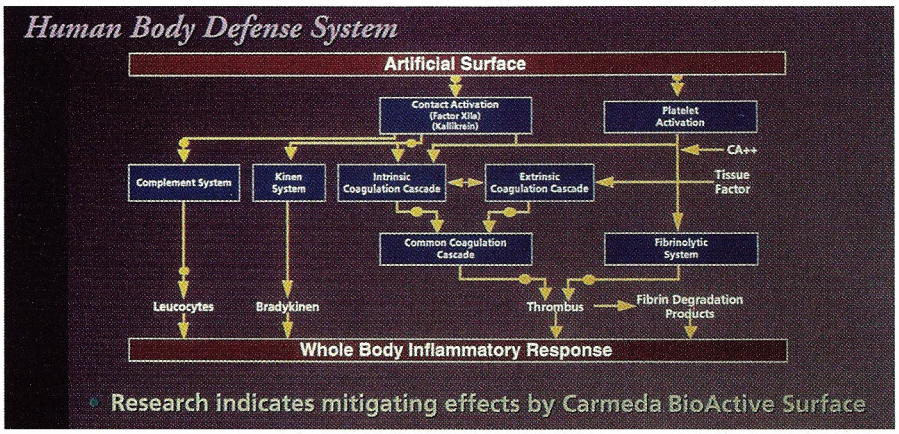

Figure 11. Carmeda (Heparin Bonding) Bioactive Surface-Effect on Human Body Defense System.

SUMMARY

Surgery for descending thoracic and thoracoabdominal aortic aneurysms, as well as acute and chronic dissections and traumatic rupture of the aorta, present a major challenge for protection of the spinal cord and kidneys. The risk factors of paraplegia/paraparesis are: emergency surgery, extensive aneurysms, dissection

and aortic cross-clamp time of greater than 30 minutes.

The blood supply of the spinal cord is by multiple input into the anterior spinal artery. The segmental branches of the aorta, namely the lower intercostal and upper lumbar arteries, are considered of significant importance. The subclavian arteries are also important for the vertebral branches supply the upper thoracic segments. The inferior and distal hypogastric arteries also supply the cauda equina.

The technical considerations that facilitate adequate spinal cord protection are stable hemodynamics, adequate spinal cord blood flow, contributed to by active distal perfusion, prevention of steal phenomena during performance of surgery and reimplantation of critical intercostal and lumbar arteries. Left atrial-femoral artery partial cardiopulmonary bypass, referrably with a centrifugal pump and heparin-bonded circuitry, will control proximal hypertension, alleviate afterload, and provide active distal perfusion. The perfusion technique will also enable rapid blood volume replacement. Proximal decompression is only optimal by partial cardiopulmonary bypass, pharmacological intervention with sodium nitroprusside is inappropriate because of resultant inadequacy of spinal cord perfusion.

Somatosensory evoked potential monitoring has been recommended for intraoperative and postoperative management. The reversal of loss of somatosensory evoked potentials can be facilitated by control of back bleeding and selective reconstruction of critical intercostal and lumbar arteries. Serial sacrifice of intercostal arteries can be conducted with somatosensory evoked potential monitoring and active distal perfusion.

The control of cerebrospinal fluid pressure can be an integral part of management accompanying somatosensory evoked potential monitoring and active perfusion. The monitoring of cerebrospinal fluid pressure and drainage to facilitate perfusion pressure of approximately 50 mm Hg and spinal pressure less than 10 mm Hg.

The conduct of the operation should include a segmental approach to reimplantation of critical intercostals as well as active distal perfusion with the initial cross-clamp above the arteria radicularis magna. The failure to reanastomose critical vessels and control of back bleeding with interruption of critical vessels may be detrimental to successful management. The placement of the cross-clamp between the left carotid and subclavian may contribute to stroke and inadequacy of spinal cord blood supply through the vertebral collaterals. In specific circumstances profound hypothermia and circulatory arrest may be optimal operative techniques. The limitation of ischemic duration should always be given consideration.

The first postoperative day requires intensive care with control of hemodynamics with avoidance of hypotension, monitoring of somatosensory evoked potentials and maintenance of adequate cerebrospinal blood flow by reduction of spinal fluid pressure with drainage of cerebrospinal fluid.

The Medtronic Biomedicus pump and Carmeda heparin bonded equipment both facilitate surgery for thoracic and thoracoabdominal aortic disease. **STI**

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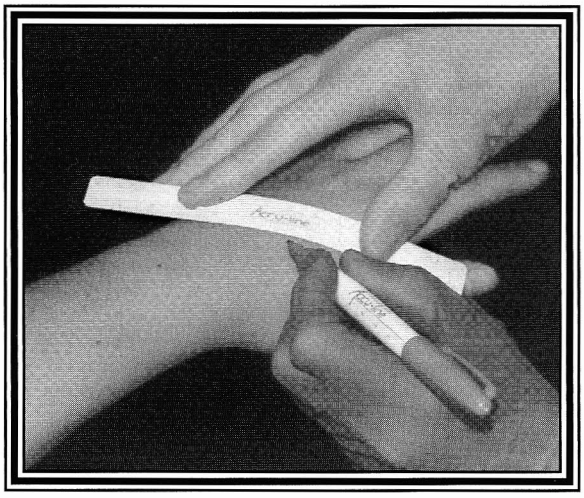

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