—Review—

Neuroprotection during Open Aortic Arch Surgery: Cerebral Perfusion Methods and Temperature

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Neuroprotection is important in open aortic arch surgery because of the dependence of brain tissues on cerebral perfusion. Therefore, several techniques have been developed to reduce cerebral ischemia and improve outcomes in open aortic arch surgery. In this review, I describe various neuroprotective strategies, such as profound and deep hypothermic circulatory arrest, selective antegrade cerebral perfusion, retrograde cerebral perfusion, and lower body circulatory arrest; compare their advantages and disadvantages, and discuss their evolution and current status by reviewing relevant literature.

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Key words: aortic arch, neuroprotection, cerebral perfusion, body temperature, cerebral ischemia

Introduction

Open aortic arch surgery requires appropriate neuroprotection because cerebral perfusion is almost entirely controlled by the three vessels branching from the aortic arch, particularly the right brachiocephalic and left common carotid arteries. Moreover, nervous tissue is extremely vulnerable to ischemic injury. Brain tissue has a very high metabolic rate and is exceptionally sensitive to ischemia because of its constant oxygen requirement to facilitate aerobic glycolysis[1]. Accordingly, the safe time limit for cerebral ischemia at normal body temperature (37°C) is 5 min[2].

Herein, I review techniques that have improved the outcomes of open aortic arch surgery regarding specific topics.

Neuroprotective Strategies during the Nascent Stages of Open Aortic Arch Surgery

In 1950, surgeons Michael E. DeBakey, Denton A. Cooley, and E. Stanley Crawford pioneered surgical techniques that contributed to an increase in thoracic aortic surgeries[3,4]. In 1957, they treated six patients with aortic dissection using cardiopulmonary bypass (CPB), and reported the first successful case of fusiform aneurysm resection in the aortic arch. Subsequently, in the 1960s, although several techniques were explored, they were later abandoned because of technical intricacies, limited surgical indications, and serious neurological complications. In 1975, Griepp et al.[5] reported the first case series of successful prosthetic replacement of the aortic arch using profound hypothermic circulatory arrest (HCA) at a temperature < 15°C. The use of packed ice around the head of patients undergoing deep HCA (DHCA) lowered the brain's surface temperature, effectively reducing neurological complications and operative mortality. The reduction in the body's metabolism induced by temperatures < 20°C and the lack of serious neurological complications in patients who safely underwent short-term circulatory arrest provided evidence suggesting that aortic arch surgery should be performed under hypothermia.

Hypothermic Circulatory Arrest

HCA was first performed in the clinical setting in 1959, by the British surgeon Charles Drew[6]. Subsequently, Griepp et al. achieved satisfactory results using the same procedure for aortic arch replacement[5].

Temperatures below 20°C significantly reduce metabolism. Providing brief intervals of circulatory arrest to perform surgeries without severe neurological complications, through cooling of the patient became a fundamental

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Table 1 Calculated Safe Duration of Hypothermic Circulatory Arrest at different temperature with regard to cerebral metabolic rate and by McCullough et al.[2] ©1999 Elsevier. Reprinted from Ann Thorac Surg. 1999; 67 (6): 1895-9.

Temperature (°C)	Cerebral Metabolic Rate (% of baseline)	Safe Duration of HCA (min)
37	100	5
30	56 (52-60)	9 (8-10)
25	37 (33-42)	14 (12-15)
20	24 (21-29)	21 (17-24)
15	16 (13-20)	31 (25-38)
10	11 (8-14)	45 (36-62)

HCA= hypothermic circulatory arrest

concept in aortic arch surgery. Numerous experimental and clinical studies examined the impact of hypothermia on ischemic tolerance in the central nervous system and tested safe time limits for HCA. Four levels of hypothermia were systematically categorized by Johns Hopkins University: mild (35-33°C), moderate (32-28°C), deep (27-21°C), and profound (<20°C) hypothermia[7].

A 1970s review reported several cases of cardiac arrest induced by deep hypothermia during open-heart surgery for congenital heart disease among infants who underwent total circulatory occlusion of at least 1 h at a temperature of 20°C without any brain damage[8]. However, limited information is available regarding adult patients undergoing DHCA for thoracic aortic repairs. Several reports[9–11] documented increased transient neurological deficits (TNDs), fine motor deficits, and extended hospital stay when the DHCA time exceeded 25 min, particularly in older patients and individuals with neurological disorders. Moreover, neurological complications were more frequent after prolonged DHCA (> 40 min) and could be transient or permanent[9–11].

To determine the safe durations of circulatory arrest, McCullough et al.[2] used the cerebral metabolic rate of oxygen consumption as an estimate and achieved comparable results of 31 min at 15°C. The data in **Table 1** suggest the interval could be extended to 45 min at 10°C.

Selective Antegrade Cerebral Perfusion (SACP)

Neuroprotection by DHCA alone is not feasible owing to the limited safe period for circulatory arrest; therefore, adjunctive protective measures are required to reduce complications associated with complex surgeries, including aortic arch replacement.

In 1956, Cooley et al. successfully used normothermic antegrade cerebral perfusion via the carotid arteries to resect a large aneurysm of the ascending aorta[3]. DeBakey et al.[4] reported the first successful use of open aortic arch surgery for a mycotic aneurysm involving the ascending aorta and transverse arch, by using normothermic cerebral perfusion via direct bilateral carotid cannulation and distal perfusion via right femoral artery cannulation. However, this technique was soon abandoned because of frequent cerebral embolism and adverse neurological outcomes. After the introduction of routine aortic arch surgery under profound hypothermia and circulatory arrest in 1975 by Griepp et al.[5], 10 years elapsed before Kazui[12] in Japan and Guilmet et al.[13] in Europe brought aortic arch aneurysm surgery to the next level. They suggested that the combination of SACP and HCA resulted in significantly fewer neurological complications[12,13]. The new neuroprotective strategy of "cold cerebroplegia" by Bachet et al. combined profound (6-12°C) selective cerebral perfusion via the carotid artery during DHCA (26°C) to increase ischemia tolerance and permit longer operation times for more complex procedures with fewer neurological complications, while simultaneously avoiding profound hypothermic core body temperatures (< 20°C)[13,14]. Kazui et al. also introduced a new perfusion technique of bilateral SACP at 22°C with excellent results[12,15].

In SACP, several variables should be considered to achieve optimal neuroprotection, namely, target cerebral blood flow (CBF), blood pressure, hemodilution, and intracranial pressure (ICP). At rest, 15% of the cardiac output is estimated to constitute normal cerebral flow[16]. Studies have highlighted the association of increased ICP and consecutive requirements for higher perfusion pressures, with cerebral injury and adverse neurological outcomes[17]. Moreover, high-flow SACP significantly increases CBF and ICP, resulting in cerebral edema with no benefit

Table 2 Suggested guidelines for selective antegrade cerebral perfusion by Spielvogel et al.[20] ©2013 Elsevier. Reprinted from J Thorac Cardiovasc Surg. 2013; 145 (3Suppl): S59-62.

Pressure	40-60 mm Hg
Flow	6-10 mL/kg/min
Temperature	
Core cooling	20°C-30°C
SACP	20°C-28°C
pH management	Alpha-stat
Hematocrit	25%-30%
Cannulation	
Unilateral vs bilateral	If SACP>30-40 min, consider bilateral
Option	Right axillary ± left CCA (occlude left ScA)
	Innominate artery ± left CCA
	Right or left CCA
	Right brachial artery
Caveats	Use NIRS monitoring
	Protect spine and corpus

SACP= Selective antegrade cerebral perfusion, CCA= Common carotid artery, ScA= Subclavian artery, NIRS= Near infrared spectroscopy.

regarding cerebral metabolism[18]. Avoiding hemodilution during SACP may prevent higher CBF and associated cerebral injury. Therefore, pump flows and pressures during SACP must be appropriately regulated. More recently, Jonsson et al.[19] reported safe minimal CBF during SACP and identified an ischemic threshold of at least 6 mL/kg/min. Based on these experimental and clinical studies, Spievogel et al.[20] reported potential indexes to develop guidelines for SACP as follows: perfusion pressure (40-60 mmHg), flow (6-10 mL/kg/min), core cooling temperature (20-30°C), and SACP temperature (20-28°C) (**Table 2**). When considering optimal CBF, another crucial variable is the autoregulation of both CBF and pressure in the physiologic spectrum under normal circumstances; however, an organism's ability to perform this function is temperature dependent and is dramatically decreased at 25°C and below[9].

The normal brain possesses an autoregulation to maintain CBF within the range of 60-50 mmHg[21]. Various physiological conditions are known to modify the autoregulation function, but the details of CBF under nonphysiological extracorporeal circulation (e.g., continuous (nonpulsatile) flow, hypothermia, and blood dilution) were unclear. Sadahiro et al.[22] compared the relationship between CBF and extracorporeal perfusion pressure under hypothermic conditions (25°C) and the impact of pulsatile perfusion in dogs. CBF determined blood flow in the superior sagittal sinus, where 43% of the blood in the entire brain was perfused[23]. It was shown that the CBF regulation function was maintained with extracorporeal circulation perfusion pressure ≥ 50 mmHg at both normal and low temperatures. Furthermore, the reduced CBF was lower than that during continuous flow even at a pulsatile flow of ≤50 mmHg. CBF was maintained even when the perfusion pressure was reduced from 90 to 40 mmHg in extracorporeal circulation under deep hypothermic (i.e., 20°C) continuous flow[24]. These animal experiments indicate that a perfusion pressure at the lower limit of the range where CBF regulation function is maintained (i.e., perfusion pressure of 40-50 mmHg) is adequate.

In 2013, Tian et al., conducted a meta-analysis comparing postoperative outcomes in aortic arch surgery using DHCA alone and SACP combined with DHCA as an adjunctive protective measure and reported that combined use was associated with significantly higher postoperative survival rates[25].

Retrograde Cerebral Perfusion (RCP)

RCP was first described by Mills and Ochsner in 1980 to treat massive air embolism during CPB[26]. In 1990, Ueda et al.[27] first described the routine use of continuous RCP in thoracic aortic surgery for neuroprotection during circulatory arrest. Thereafter, RCP was widely adopted, especially in aortic surgery, despite limited evidence regarding its efficacy or safety. RCP is instituted using both bicaval and arterial cannulation. Despite the conflicting results of clinical and animal studies[27-36], possible mechanisms underlying the neuroprotection afforded by RCP include providing metabolic substrates, purging gaseous and particulate emboli from cerebral blood vasculature, and maintaining cerebral hypothermia. A pressure of 25 mmHg is required to maintain adequate perfusion, and a flow rate of 150-300 mL/min is recommended to flush metabolic products and embolic debris[37,38]. Coselli and LeMaire[39] investigated 479 patients and reported lower mortality and stroke rates in those who underwent DHCA with RCP compared to those who did not. Safi et al.[40] also demonstrated that RCP exerted a protective effect against stroke. Many of these studies suggest that the adjunctive use of RCP during DHCA as a neuroprotective strategy, is more effective than using DHCA alone, at least in open aortic arch surgery.

Selective Antegrade Cerebral Perfusion versus Retrograde Cerebral Perfusion

During the 1990s to 2000s, two major trends were observed in neuroprotective strategies for open aortic arch surgery: one recommending the use of SACP and another the use of RCP. Several comparative studies aimed to determine which strategy was more effective. In Japan, besides Ueda et al.[41] who first introduced RCP in aortic arch surgery, excellent postoperative outcomes reported by Kazui et al.[42] using SACP and Okita et al.[43] using RCP in large patient populations contributed to heated but polite debate.

Although many retrospective studies have been conducted on DHCA with RCP and SACP, randomized comparative studies are scarce. Okita et al.[44] evaluated data from 60 consecutive total arch replacements allocated randomly to DHCA with RCP or SACP and concluded that both combinations resulted in acceptable levels of mortality and morbidity, but the prevalence of TNDs was significantly higher in DHCA with RCP. A randomized controlled trial (RCT) by Tanoue et al.[45] involving 32 patients who underwent either SACP or RCP (17 and 15 patients, respectively) revealed that CBF was significantly better in SACP than in RCP. Importantly, only three patients showed signs of CBF reversal, and this low number could be attributed to the pressure utilized in the RCP circuit (15-25 mmHg). Furthermore, the duration of cerebral perfusion was 71 and 38 min in the SACP and RCP groups, respectively (p=0.0047). Nevertheless, the clinical outcomes did not differ between the groups. A recent RCT by Svensson et al.[46] on 121 patients who received either RCP (n=60) or SACP (n=61) during total arch replacement revealed no superiority of SACP over RCP; both produced similar neurologic outcomes. The circulatory arrest times for SACP and RCP were 31±14 and 26±12 min, respectively, with no difference in clinical outcomes. In the RCT by Tanoue et al., although the cerebral circulation time for SACP was significantly longer, no differences were observed in postoperative outcomes.

Okita et al.[47] conducted a comparative analysis of 8,169 cases selected from among 16,218 cases of aortic arch surgery performed between 2009 and 2012, obtained from the Japan Adult Cardiovascular Surgery Database, after excluding patients with acute aortic dissection, with ruptured aneurysms, or who underwent emergency surgery. For neuroprotection, 7,038 patients underwent SACP and 1,141 underwent DHCA with or without RCP. A nonmatched comparison was made between the groups, and propensity score analysis was performed among 1,141 patients. The matched-paired analysis revealed that the minimum rectal temperature was lower in the DHCA group, with or without RCP (21.2±3.7°C vs. 24.2±3.2°C) and that the duration of CPB and cardiac ischemia was longer in the SACP group. However, no significant differences were observed between the SACP and DHCA with RCP groups regarding 30-day mortality (3.2% vs. 4.2%), hospital mortality (6.0% vs. 7.1%), incidence of stroke (6.7% vs. 8.6%), or TNDs (4.1% vs. 4.4%). Moreover, no composite outcome was observed for hospital mortality, bleeding, prolonged ventilation, need for dialysis, and infection (SACP 28.4% vs. DHCA with or without RCP 30.1%). However, DHCA with or without RCP resulted in a significantly higher rate of prolonged intensive care unit stay (>8 days: 24.2% vs. 15.6%). Therefore, SACP might be the preferred neuroprotection method for complicated aortic arch procedures. A recent meta-analysis of 5,060 patients from 15 studies by Hu et al.[48] also revealed that the incidence of postoperative stroke and TNDs was similar between SACP and RCP.

These data indicate the lack of clear evidence supporting the superiority of either SACP or DHCA with RCP in terms of neuroprotection[49]. Nevertheless, RCP combined with DHCA might offer a safe time limit for antegrade cerebral circulatory arrest. While many studies[27–29,35,36] indicate a circulatory arrest time of approximately 30 min for this adjunctive technique, determining the differences between the two methods within such a timeframe might be difficult. In SACP, antegrade cerebral perfusion is maintained, at least during surgery. This would reassure surgeons who perform complex and time-consuming open arch surgeries, as the cerebral circulatory arrest time would be very short.

The most important advantage of SACP is that it provides extended time, allowing delicate repair of complicated arch aneurysms. Indeed, there is a growing international trend toward using SACP over RCP. This is anecdotally based on evidence suggesting the likelihood of providing sufficient cooling rather than adequate nutrition to the brain[50]; higher perfusion pressure may contribute to increased ICP and ultimately cerebral edema[51]. Therefore, in complex aortic procedures, SACP is preferred over RCP, as supported by several studies[49,52].

Deep to Moderate Hypothermia and SACP

The complications associated with deep hypothermia promoted research to improve outcomes in open aortic arch surgery using lesser degrees of hypothermia. Moreover, because of the potential side effects of deep or profound hypothermia on CPB, the possibility of performing open aortic arch surgery using warmer temperatures with SACP has garnered interest. Despite the absence of experimental data confirming the safety of higher core body temperatures, the preference for more moderate temperature management is motivated by the incentive to avoid potential hypothermia-associated complications and to reduce CPB time, postoperative bleeding, and blood transfusion requirement in the clinical setting as well as to reduce endothelial cell dysfunction and neuronal apoptosis in the experimental setting[53–56]. Encouraged by the success of SACP in routine cases, many surgeons aimed for higher CPB and SACP perfusate temperatures[49,53,54]. Initial clinical results suggest that higher degrees of hypothermia enable sufficient neuroprotection during SACP[51]. However, the adjusted degree of hypothermia during aortic arch surgery should always provide sufficient protection to lower body organs. In 2007, Pacini et al.[57] reported the outcomes of 305 aortic arch surgeries either with deep-to-profound (<22°C) or deep hypothermia (up to 26°C) with average SACP times up to 60 min. No intergroup differences were observed in 30-day mortality (12.7 vs. 13.8%), permanent neurological deficit (PND) (3.1 vs. 1.7%; p=0.72), and TND (7.9 vs. 8.6%). Pacini et al.[58] reported excellent outcomes of 95 patients (≥75 years) who underwent SACP at 20°C and lower body circulatory arrest (LBCA) for 24 min at 25°C. Prolonged LBCA (>40 min) and femoral cannulation site were significant risk factors for postoperative mortality and neurological complications. Kamiya et al.[53], in a propensity score-matched analysis of 377 patients, found no significant differences in mortality or morbidity between deep and moderate LBCA, in the study or propensity score-matched cohort. These results suggest that moderate LBCA can be safely performed for aortic arch repair and postoperative inflammatory responses tended to be lower in patients undergoing moderate LBCA than in those undergoing deep LBCA. Zierer et al.[59] performed a single-center study on 1,002 patients undergoing SACP with mild (28-30°C) hypothermic arrest for arch replacement and found that SACP made deep hypothermia nonessential for aortic arch replacement. Their results suggested that SACP and mild HCA can be safely applied in complex aortic arch surgeries in a subgroup of patients with up to 90 min of SACP.

A recent survey revealed that two-thirds of European centers preferred bilateral SACP over unilateral perfusion because of concerns about patients who possess an incomplete circle of Willis[60–62]. Tian et al.[63] performed a meta-analysis of nine studies (comprising 1,846 patients) directly comparing unilateral versus bilateral SACP and found that the average circulatory arrest time, cerebral perfusion time, and circulatory arrest temperature were similar, with no statistically significant intergroup differences in mortality, TND, or PND. Unilateral SACP provides better exposure and decreased manipulation of the cerebral vessels, possibly resulting in decreased embolism. Concerns with bilateral SACP include technical complexity and risk of embolic complications, either directly from antegrade perfusion or from manipulation of the arch vessels. Despite promising results obtained using unilateral SACP, most surgeons prefer bilateral perfusion, particularly in longer surgeries[20,51,62].

Some reports showed bilateral perfusion to be more effective than unilateral perfusion when SACP is extended. Krähenbühl et al.[64] followed up 292 patients with post-aortic arch surgery performed with deep hypothermic circulatory arrest and unilateral or bilateral cerebral perfusion. The 36-Item Short Form health survey questionnaires administered at midterm follow-up revealed that patients whose SACP times exceeded 40 min exhibited better quality of life if they underwent bilateral SACP. Malvindi et al.[65] performed a meta-analysis involving 3,548 patients. By using a neurologic injury rate threshold of <5%, 30-50 min of unilateral perfusion was acceptable, whereas bilateral perfusion permitted 86 to >164 min. Consequently, the authors[60,61] recommended using bilateral perfusion for anticipated SACP interval > 50 min.

Clinical evidence suggests that prolonged LBCA poses a risk of neurological complications, particularly permanent spinal cord injury; however, some surgeons propose even higher temperatures to shorten the duration of surgeries. Urbanski et al.[66] analyzed 347 patients who under-

Table 3 A safe ischemic interval for the spinal cord can be estimated by several studies [9 53 59 68 70] ©2014 Oxford University Press. Reprinted from Eur J Cardiothorac Surg. 2014 Jan; 45 (1): 27-39.

(I) 20 min at normothermia (37°C)
(II) 50 min at mild hypothermia (32°C)
(III) 75 min at moderate hypothermia (28°C)
(IV) 120 min at deep hypothermia (20°C)

went SACP and moderate-to-mild LBCA of up to 31.5°C (range: 26.0-35.0°C) for an average duration of 18 min during hemiarch repairs (n=270) and 29 min during total arch replacement (n=77). Postoperatively, 5 of the 347 patients required dialysis and 1 had bowel ischemia; the 30-day mortality (0.9%) and neurological complications (PND, 2.3%; TND, 0.9%) were remarkably low, with no occurrence of paraplegia. Leshnower et al.[67] retrospectively compared outcomes after elective and emergent hemiarch replacements with SACP for 25 min at deep and moderate temperatures (24.3 vs. 28.6°C); their propensity score-matched analysis revealed significantly fewer PNDs (2.5 vs. 7.2%) in the moderate group, with no significant differences in bleeding, TND, or renal failure between the groups. However, since they only studied hemiarch replacement—a relatively simple surgery—and since the circulatory arrest time was 25.8 min vs. 25.3 min, assessing the effect of the aforementioned temperatures within such timeframes was difficult.

Ischemic Tolerance of the Spinal Cord and Abdominal Viscera during LBCA

Nervous tissue is most susceptible to warm ischemia. The radical changes involved in temperature management to maintain moderate-to-mild core body temperatures pose a significant risk of spinal cord ischemic injury and neurological damage ranging from temporary paraparesis to irreversible permanent paraplegia[50]. Fortunately, postoperative neurological and visceral complications after SACP and deep-to-moderate hypothermic arrest up to 30 min are rare; however, lower body ischemic tolerance at moderate or even mild hypothermia remains unknown.

In 2004, Strauch et al. published an experimental porcine study to determine whether mild hypothermia offers protection against spinal cord ischemic injury[68]. They demonstrated that spinal cord ischemic tolerance was significantly prolonged when cooling from normothermia (36.5°C) to mild hypothermia (32.0°C) before aortic cross-clamping. Cross-clamping during normothermia was limited to 20 min, and mild hypothermia increased spinal cord ischemic tolerance up to 50 min. However, 25 min of normothermia and 60 min of mild hypothermia resulted in paraplegia. Subsequently, Griepp et al. conducted a similar porcine study and showed that even 90 min of profound hypothermia (15°C) did not impair motor function[69].

Regarding the risk of prolonged LBCA in aortic arch surgery[53], Etz et al. aimed to define spinal cord ischemic tolerance at moderate core body temperatures in a porcine SACP model[70]. They used previous spinal cord ischemic tolerance data to generate a logarithmic plot of core body temperature vs. SACP time to define a possible safety margin for LBCA at moderate hypothermia of 28°C. An experiment based on these assumptions aimed at proving that prolonged SACP and LBCA for 90 min was safe while moderate core body temperatures for 120 min resulted in permanent paraplegia failed to confirm the safety of this approach in most animals in the 90-min group (postoperative mortality: 60% and paraplegia rate: 100% in the remaining animals). Therefore, the initial assumption that 90 min of moderate hypothermia at 28°C in combination with SACP may be safe for the spinal cord had to be corrected. Using the aforementioned experimental and clinical study findings[49,53,55,59,62,64,66,70], Luehr et al.[9] summarized the safe time periods for spinal cord injuries (**Table 3**) based on the relationship between spinal cord ischemia time and temperature.

Abdominal visceral ischemic damage during elective aortic arch surgery at deep hypothermic temperatures was uncommon in the past, because the ischemic tolerance of the abdominal viscera most likely exceeded that of the spinal cord at a given core body temperature. In the study by Etz et al.[70], most animals died during the first 24 h because of multiorgan failure or respiratory insufficiency after ischemic injury. Significant injury to the abdominal viscera appears to occur at 90 min during SACP and LBCA; a duration of 120 min may result in fatal multiorgan ischemic injury. Khaladj et al.[71] compared 60 min of moderate (30°C) or profound (20°C) HCA on visceral end-organ function in a porcine model. Higher circulating lactate levels during reperfusion and histological evidence of more pronounced edema formation within the bowel wall in the moderate hypothermia group (30°C) indicated less-effective organ protection at 30°C than that at 20°C after 6 min of HCA.

Clinically, among the visceral organs, the kidneys are the most sensitive to ischemia, followed by the liver and bowel[72,73]. The clinical impact of ischemic damage to each organ varies and depends on the treatment modality.

Comments

In Japan, 2,198 aortic arch surgeries (excluding dissections) were performed in 2018, with an overall hospital mortality of 3.0% (n=67), showing a positive trend in postoperative outcomes[74]. In 1986, Kazui et al. reported the results of open aortic arch surgery using DHCA with SACP, which garnered worldwide interest. Moreover, in 1990, Ueda et al. first introduced the use of RCP with DHCA in aortic arch surgery and reported good results. Subsequently, studies reporting favorable outcomes in open aortic arch surgeries using either SACP or RCP have been regularly published. Despite clear evidence showing that SACP is more effective than RCP, a trend towards a gradual increase in body temperature in aortic arch surgeries has been recently observed owing to concerns regarding prolonged CPB time in deep hypothermia and organ damage caused by bleeding and tissue inflammatory reactions. The main assumption underlying the use of RCP is that it should be performed in conjunction with DHCA; the body temperature cannot be increased while maintaining neuroprotection. SACP provided surgeons adequate time to perform complex surgeries, therefore, this method gradually became the main technique for neuroprotection during aortic arch surgery.

Recently, body temperature management during LBCA has been widely discussed. While SACP is generally performed with a core temperature of ～25°C, more studies are reporting SACP at progressively higher temperatures (25°C→28°C→30°C). When using SACP, in addition to ensuring the optimal management of cerebral perfusion temperature, flow, and pressure, spinal cord ischemic tolerance and the effects on lower body organs have to be considered. In this review, spinal cord ischemic tolerance time is presented in relation to temperature (**Table 3**)[9]. It is reasonable to conclude that LBCA may be performed safely within the ranges presented here, since concerns regarding spinal cord ischemic tolerance are more important than those concerning other abdominal visceral organs.

According to Okita[75], improvement in operative outcomes of aortic arch surgery over the last few decades is because of the advances in surgical techniques and extracorporeal circulation devices and increased knowledge about the circulatory mechanisms in the brain and other organs. However, in today’s aging society, older patients are requiring open aortic arch surgery. Therefore, white matter hyperintensities (leukoaraiosis) frequently observed on T2-weighted and/or fluid-attenuated inversion recovery images of the brain of older patients are significant predictors of TNDs and watershed stroke. In addition, leukoaraiosis is significantly correlated with watershed infarction[76]. Accordingly, Okita advises that leukoaraiosis is a significant independent factor for neurological dysfunction associated with open aortic arch surgery and that further research is required to reduce the high incidence of TNDs.

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