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REVIEW

Modern temperature management in aortic arch surgery: the dilemma of moderate hypothermia

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Summary

Arch surgery is undoubtedly among the most technically and strategically challenging endeavours in aortic surgery, requiring thorough understanding not only of cardiovascular physiology, but also in particular, of neurophysiology (cerebral and spinal cord), and is still associated with significant mortality and morbidity. In the late 1980s, when deep hypothermic circulatory arrest (HCA) had gained widespread acceptance as the standard approach for arch surgery, antegrade selective cerebral perfusion (SCP), as an adjunct to deep HCA, began its triumphal march, offering excellent neuroprotection and improved overall outcome. This encouraged the use of antegrade SCP in combination with steadily increasing body core temperatures—a trend culminating in the progressive advocation of moderate-to-mild temperatures up to 35°C, and even normothermia. The impetus for progressive temperature elevation was the limitation of adverse effects of profound hypothermia and the most welcome side effect of significantly shorter cooling and rewarming periods on cardiopulmonary bypass (CPB), and thereby, potentially, the alleviation of the systemic inflammatory response and, in particular, the risk of severe postoperative bleeding (and other organ dysfunctions). The safe limits of prolonged distal circulatory arrest, particularly with regard to the ischaemic tolerance of the viscera and the spinal cord, have not yet been clearly defined. Adverse outcomes due to inappropriate temperature management (core temperatures too high for the required duration of distal arrest) are probably highly underreported. Complications historically associated with hypothermia, namely excessive bleeding, are possibly overestimated. Trading effective neuroprotection and excellent outcomes for the risk of prolonged 'warm' distal ischaemia might constitute a significant step back, jeopardizing visceral and, in particular, spinal cord integrity, with unpredictable consequences for long-term outcome and quality of life, particularly affecting those in need of more complex surgery or with previous neurological deficits.

Keywords: Aortic arch surgery • Hypothermic circulatory arrest • Moderate hypothermia • Antegrade selective cerebral perfusion • Cerebral protection • Spinal cord ischaemia • Visceral organ ischaemia

INTRODUCTION

Surgery for complex aortic pathologies, such as acute dissections and aneurysms involving the transverse arch, remains one of the most technically challenging endeavours of modern aortic surgery. The introduction of profound hypothermia—allowing for short periods of complete circulatory arrest—in the mid-1970s by Borst and Griepp paved the way for modern arch surgery requiring prolonged ischaemic tolerance of the central nervous system [1]. The introduction of antegrade selective cerebral perfusion (SCP) by Bachet and Kazui in the late 80s finally made transverse arch surgery a considerably safe and standardized procedure [2–4].

More recently, a new concept—based on the euphoria with the outstanding neuroprotective effects of antegrade SCP—progressively advocating SCP and distal arrest in combination with significantly higher body core temperatures (up to 35°C) has been introduced to avoid the complications attributed to deep hypothermia and prolonged extracorporeal circulation [5–7].

The safe limits of prolonged distal circulatory arrest at higher temperatures—particularly with regard to the ischaemic tolerance of the viscera and the spinal cord—have not yet been clearly defined and are therefore not well recognized in clinical practice. However, this new temperature management concept of moderate or even mild hypothermic circulatory arrest (HCA) is inevitably associated with prolonged durations of lower body ischaemia at relatively warm temperatures, evoking an unpredictable risk for the abdominal viscera and the spinal cord. Despite these potentially fatal risks, this new concept is progressively being introduced into clinical use and enjoys widespread acceptance, even in centres with limited experience and a consecutively much higher risk of prolonged distal arrest times.

This article reviews current state-of-the-art of neuroprotective strategies in aortic arch surgery, focusing on the benefits of hypothermia and cold antegrade SCP. Recent developments, antegrade SCP particularly, and the current trend to tolerating mild-to-moderate hypothermia during distal arrest, are thoroughly discussed in the context of new experimental and recent clinical studies.

HYPOTHERMIC CIRCULATORY ARREST

In the middle of the 20th century—when cardiopulmonary bypass (CPB) and extracorporeal circulation had just been utilized for the first time in aortic surgery—open repair of the transverse arch still remained an almost impossible undertaking only a few surgeons would dare to attempt. During the late 1950s, Michael E. DeBakey, E. Stanley Crawford and Denton A. Cooley in Houston developed new surgical techniques to address aortic pathologies of the ascending, the descending and the thoracoabdominal aorta, and also—the transverse arch [8]. In 1955, they were also the first to report on 6 cases of aortic dissection treated by aggressive surgery, and the first to resect a fusiform aortic arch with the use of CPB in 1957 [9]. During the 50s and 60s, various innovative technical approaches were developed for surgery of the transverse arch, but were all abandoned due to high complexity, limited surgical indications and increased risk of neurological complications.

In 1964, Borst and colleagues described the closure of an arterio-venous fistula in Munich— caused by a bullet from World War II that had found its way to the mediastinum and injuring both the aorta and the pulmonary artery—for the first time in profound HCA [10]. One decade later, the first series of routine aortic arch operations using profound (<15°C) HCA was published by Griepp *et al.* [1]. Additional cerebral protection was achieved via surface cooling—by packing the head in ice—to minimize cerebral metabolism, permitting complete aortic arch replacement with significantly lower rates of neurological complications and reduced postoperative mortality [1].

Since temperatures below 20°C significantly decrease metabolism, allowing for brief intervals of circulatory arrest to perform surgery without severe neurological complications, thorough cooling of the patient became the basic concept of aortic arch surgery. Since then, numerous experimental and clinical studies focused on the impact of hypothermia with regard to the ischaemic tolerance of the central nervous system to determine the safety margins of this concept.

Systemic hypothermia and hypothermic circulatory arrest

Systemic hypothermia reduces the metabolic tissue rate and is generally employed for neuroprotection during cardiac and aortic surgeries, still 'the complexity of the surgical repair, age and overall medical status of the patient, and the surgeon's preference are all factors that determine the desired level of hypothermia' [11]. Four different levels of systemic hypothermia have been systematically categorized by the Johns Hopkins group around Duke E. Cameron according to physiological findings: mild (35–33°C), moderate (32–28°C), deep (27–21°C) and profound (<20°C) [11, 12] (Table 1).

Since nerve tissue is most susceptible to ischaemia, the respective level of hypothermia during aortic arch surgery should be chosen as required to achieve sufficient neurological protection. Cerebral metabolism is progressively depressed by approximately 6–7% per 1°C decline in temperature [12]. The brain's electrical activity starts to decrease at mild hypothermia (<33.5°C) until no further electrical activity can be detected by electroencephalography at profound hypothermic temperatures (19–20°C) [12]. Accordingly, cerebral oxygen consumption is related to temperature and—if compared with normothermia (37°C)—can be reduced by >50% at 28°C (moderate hypothermia), >80% at 18°C (profound hypothermia) and almost 90% at 8°C (ultra profound hypothermia), respectively [13].

HCA alone—if consequently applied—is sufficient to significantly prolong the 'safe' ischaemic time up to 10 times.

Table 1: The four stages of hypothermia with regard to clinical and physiological characteristics [11, 12]

Level of hypothermia	Temperature range (°C)
Mild	35.9–33.0
Moderate	32.9–28.0
Deep (severe)	27.9–21.0
Profound	<20.9

The limitations of hypothermic circulatory arrest

Despite the protective effects of HCA during aortic arch surgery for all tissues affected by circulatory arrest, its safe use is limited due to various reasons. Consequently, the early assumption that deep HCA can be performed safely without any neurological complications had to be revised [14]. Particularly in the elderly, durations of deep HCA >25 min have been shown to cause transient neurological dysfunction (TND), fine motor deficits and prolonged hospital stay [15, 16]. Moreover, severe TND has been correlated with loss of cognitive function up to 6 weeks postoperatively [17]. Experimental and clinical metabolic studies suggest that cerebral metabolic suppression at clinical levels of deep hypothermia is less complete than had been assumed previously [18–20].

In 1999, McCullough *et al.* [18] estimated the cerebral metabolic rate by oxygen consumption ($CMRO_2$) in 37 patients sampling blood gained from the left carotid artery and from the jugular venous bulb during HCA using the equation:

$$CMRO_2 = \frac{CBF \times \text{cerebral arteriovenousoxygen content difference}}{100}.$$

By using the temperature coefficient Q10—the ratio of metabolic rates at temperatures 10°C apart—and optimistically assuming that there is a 5-min tolerance for circulatory arrest at normothermia (37°C), the authors estimated the safe durations of circulatory arrest at various temperatures as follows: 9 min at 30°C, 14 min at 25°C, 21 min at 20°C, 31 min at 15°C and 45 min at 10°C [18] (Table 2). More recently, Fischer *et al.* [21] showed that, after 30 min of profound HCA at 15°C, the regional oxygen saturation of the frontal cortex drops below the threshold of 60% with an increased risk of severe adverse outcome ($P = 0.038$) and prolonged hospital stay following aortic arch surgery.

Prolonged circulatory arrest, even in deep hypothermia, may be associated with organ dysfunction, such as postoperative renal impairment [22]. The opponents of deep HCA argue that it causes coagulation disorders and significant postoperative bleeding [22]—however, scientific evidence for this claim is scarce and unequivocal at best [23]. Milewski *et al.* [24] compared 776 patients who underwent open aortic arch surgery with either profound HCA (<20°C) or deep HCA (21–26°C). They found that the reoperation rate for bleeding was not significantly different between both

Table 2: Calculated safe durations of HCA at different temperatures with regard to the cerebral metabolic rate by McCullough *et al*. [18]

Temperature (°C)/level of hypothermia	Cerebral metabolic rate (% of baseline)	Calculated safe duration of HCA (min)
37 (normothermia)	100	5
30 (moderate)	56 (52–60)	9 (8–10)
25 (deep)	37 (33–42)	14 (12–15)
20 (profound)	24 (21–29)	21 (17–24)
15 (profound)	16 (13–20)	31 (25–38)
10 (ultra profound)	11 (8–14)	45 (36–62)

groups (profound vs deep HCA: 3.8 vs 4.3%; $P = 0.783$). Studies comparing mild-to-moderate with deep hypothermia with regard to postoperative bleeding are not available yet.

Coagulation disorders have been reported in the literature [25], however, postoperative bleeding seems to be more related to operation time and the use of prolonged extracorporeal circulation than the stage of hypothermia [26]. The proponents of HCA believe coagulation disorders following CPB and HCA are related to platelet dysfunction that can easily be reversed by adequate transfusion of donor pool platelets alone or with platelet stabilizers [27, 28]. However, the issue of postoperative bleeding following HCA might be multifactorial—and aortic disease itself has been shown to be associated with coagulopathy [26]. This remains controversial since clinical reports on bleeding after HCA are difficult to compare [23]. The lack of 'immediate visual feedback' when dissecting tissue and small vessels during circulatory arrest might cause the impression that HCA 'triggers' bleeding. Harrington *et al*. [23] did not find an increased occurrence of postoperative bleeding following deep hypothermia, and therefore, stressed the need for further clinical studies. In contrast, some surgeons see an increased risk of coagulation disorders and multiorgan failure due to prolonged visceral ischaemia during warm distal circulatory arrest [29]. The need for prolonged CPB certainly is another inevitable factor for various physiological alterations, including epithelial permeability, oedema formation or organ malperfusion [22]. Moreover, cerebral autoregulation during cooling may only be maintained by an increase in vascular resistance until deep temperatures of approximately 22–25°C [12, 13]. Thereby, extracorporeal circulation results in a 'luxury' perfusion of the brain—with a risk of increased intracerebral pressures that ultimately may result in endothelial damage and cerebral oedema [13].

Neurological complications occur more frequently following prolonged deep HCA with durations >40 min and may be transient (TND; confusion, delirium, seizures, etc.) or permanent (PND; haemiparesis, haemiplegia, aphasia, etc.) [16, 17]. Not surprisingly, deep HCA for more than 65 min is associated with a significantly increased postoperative mortality [18]—a finding that is confounded by the fact that the duration of HCA is frequently linked to the complexity of the procedure.

pH management during cardiopulmonary bypass

The pH management during CPB and HCA is another challenging aspect of aortic arch surgery and remains a controversial subject since the optimal pH of most enzymatic reactions does vary with temperature.

Alpha-stat management is based on the concept that the pK of the histidine imidazole group changes with temperature as much as physiological blood buffers do. However, this group's ionization state—which is a key requirement for intracellular protein function—remains during cooling and, therefore, is believed to allow for normal protein charge states and function, even at low temperatures [30]. Additionally, alpha-stat pH management preserves cerebral autoregulation [14, 30].

During pH-stat management, the total carbon dioxide content of the blood is increased to maintain fixed temperature-corrected pH values during cooling, leading to cerebral vasodilatation. The proponents of pH-stat management emphasize that increased cerebral perfusion with oxygenated blood and a more homogeneous cooling might be advantageous, but increased flows also evoke the increased risk of embolism and oedema formation [31]. Moreover, the continuous administration of carbon dioxide during pH-stat promotes a state of relative acidaemia that could lower enzymatic reaction rates [30].

It remains unclear which pH strategy provides superior cerebral protection during hypothermia, particularly in the case of circulatory arrest or abnormal perfusion states [30]. However, most aortic surgeons generally apply alpha-stat pH management for adults undergoing CPB and deep HCA in order to maintain cerebral autoregulation and metabolic suppression, and to limit cerebral embolic load [30, 32]—while pH-stat is used more frequently in neonatal and infant cardiac surgery where aortopulmonary steal often exists and embolic load is low.

Though HCA preserves tissue integrity during unavoidable periods of interrupted blood flow, it requires profound temperatures (<20°C) associated with prolonged cooling and rewarming periods on CPB. As reliable cerebral protection can only be achieved for durations of <30 min with profound HCA—despite the above-mentioned limitations—additional neuroprotective strategies were developed in the 80s and early 90s.

SELECTIVE CEREBRAL PERFUSION

In 1956, the Houston group successfully used normothermic antegrade cerebral perfusion via the carotid arteries to resect a large aneurysm of the ascending aorta [33]. The first successful attempt to perform open aortic arch surgery for a mycotic aneurysm involving the ascending aorta and the transverse arch, using normothermic cerebral perfusion via direct cannulation of both carotid arteries and distal perfusion via cannulation of the right femoral artery, was reported by De Bakey *et al*. [9] 1 year later (Fig. 1). However, this technique of normothermic antegrade cerebral perfusion via bicarotid cannulation was soon abandoned due to frequently experienced arterial embolism and adverse neurological outcome.

The next milestone in the evolution of modern aortic arch surgery—after the introduction of routine open surgery under profound hypothermia and circulatory arrest in 1975 [1]—was successfully introduced into the clinical arena by Guilmet and Bachet in Europe and by Kazui in Japan in 1986: the principle of antegrade SCP in combination with HCA resulted in a significantly reduced incidence of neurological complications [34, 35].

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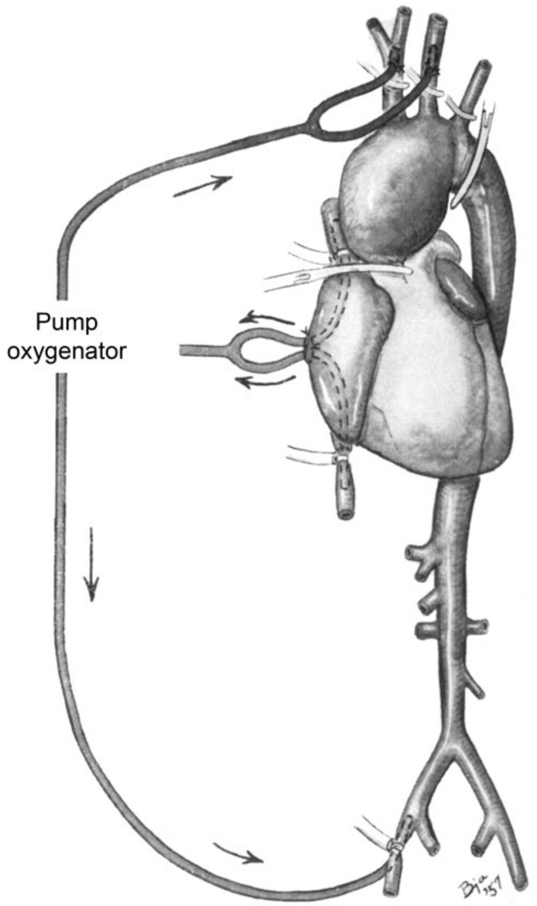

Figure 1: Technique for direct cannulation of the brachiocephalic trunk and the left common carotid artery for the administration of normothermic antegrade cerebral perfusion during open aortic arch replacement with a homograft by De Bakey *et al*. [9]. Additional lower body perfusion is achieved via direct femoral artery cannulation. (Reprinted from De Bakey *et al.* [9], with permission from Elsevier.)

The new neuroprotective strategy of 'cold cerebroplegia' by Bachet and Guilmet comprised profound (6–12°C) SCP via the carotid arteries during circulatory arrest in deep hypothermia (26°C), allowing for longer operation times in more complex procedures with lower neurological complications, while avoiding profound hypothermic body core temperatures (<20°C) at the same time [4, 34]. In the same year, Kazui introduced his new perfusion technique of bilateral SCP at 22°C in Japan with excellent results in the following years [35, 36]. In 1986, almost simultaneously, the Stanford group published their experience with antegrade SCP (unilaterally via a 14-F cannula directly into the innominate artery with occlusion of the left carotid and left subclavian arteries in 6 patients, unilaterally via the left carotid in 1 and bilaterally in 3 via the innominate and the carotid arteries simultaneously) during low-flow CPB (30 ml/kg/min) at 26–28°C [37]. During the procedure, simultaneous distal aortic perfusion was achieved via a 20-F cannula in the femoral artery that was connected via a Y-connector to the SCP line [37]—a safety measure also used by Kazui and Bachet [2, 36]. Frist *et al.*, after publishing on their first 10 patients with this technique, did not pursue their promising new method—which resembles contemporary perfusion techniques—at that time despite low neurological complications [37].

Cerebral blood flow and intracranial pressure during selective cerebral perfusion

Fifteen percent of the total cardiac output at rest is estimated to constitute normal physiological cerebral blood flow (CBF) of approximately 55 ml/min/100 g of cerebral matter [38]. To ensure optimal cerebral protection during SCP target CBF, blood pressure, haemodilution and the (counteracting) intracranial pressure (ICP) are crucial variables that must be carefully monitored.

Halstead *et al*. [39] compared ICPs of 50, 70 and 90 mmHg during SCP and deep HCA (20°C) and showed that higher ICP with increased CBF may result in cerebral injury and poorer neurological outcome. In another experimental study, Haldenwang *et al*. [40] compared different flow rates during SCP and deep HCA (25°C), showing that high-flow SCP significantly increases CBF and ICP resulting in cerebral oedema with no benefit for cerebral metabolism. The avoidance of haemodilution during SCP may also prevent higher CBF and associated cerebral injury. More recently, Jonsson *et al*. [41] reported on their experimental results of the safe minimal CBF during SCP and suggested an ischaemic threshold of at least 6 ml/min/kg. Therefore, most surgical groups using SCP perfuse the brain at a rate of approximately 8–12 ml/min/kg of body weight (0.6 ml/min/g of cerebral tissue) and a perfusion cerebral oximetry pressure of 40–60 mmHg at temperatures between 23 and 28°C [14, 23, 38, 42].

Physiologically, CBF depends on autoregulation, which is normally maintained for a wide spectrum of arterial pressures (mean 50–150 mmHg) to ensure optimal cerebral perfusion and metabolism [38]. Cerebral autoregulation is usually maintained by an active increase in vascular resistance until cooling temperatures <25°C are reached [12].

Several experimental studies showed that SCP alone or in combination with HCA offers improved neurological results when compared with HCA alone [20], or if compared with retrograde cerebral perfusion (RCP) and HCA [23, 43]. Moreover, it had been experimentally demonstrated that the neuroprotective effect of SCP is improved with profound (10–15°C) rather than warmer (20–25°C) temperatures of the perfusate [44]. Driven not only by pure medical considerations (and possibly to some degree even for economic reasons—with the rationale of shortening operation times), a trend towards much higher temperatures for CPB and distal aortic perfusion during SCP often combined with almost mild-to-normothermic perfusate temperatures is currently evident.

Unilateral vs bilateral selective cerebral perfusion

The combination of SCP and HCA became the established standard strategy for transverse arch surgery in the past decade. Antegrade SCP may be performed by direct vessel cannulation, via balloon occludable perfusion catheters, via a prosthetic graft anastomosed to the target vessel or via the 'island technique' in which an island of native aortic tissue, including the supraaortic branches, is spared and subsequently anastomosed into a prosthetic graft [19, 42, 45] (Fig. 2). However, many surgeons still favour direct aortic or femoral artery cannulation for a variety of aortic pathologies involving the transverse arch with the necessity of establishing SCP [19].

Controversies exist in the application of uni- or bilateral cerebral perfusion, particularly with regard to regional pathologies:

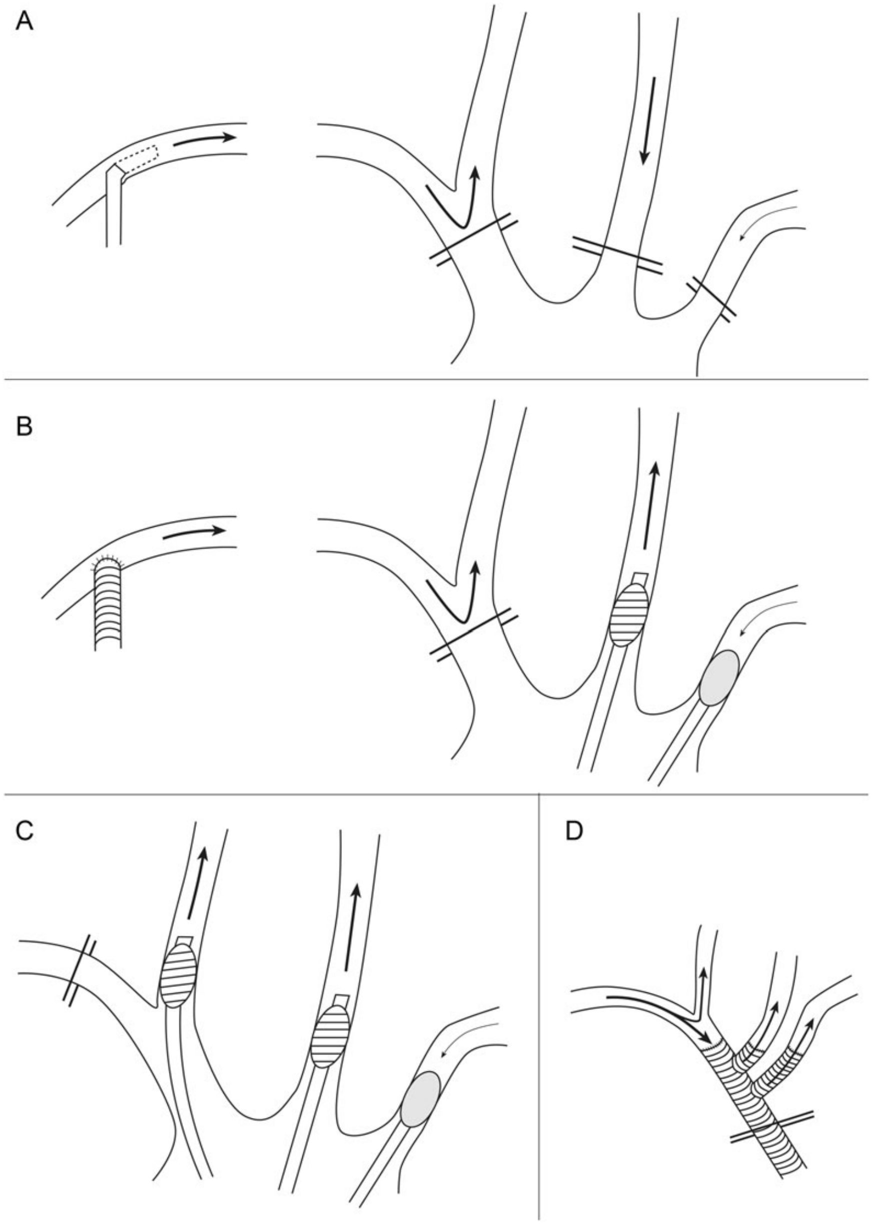

Figure 2: Various techniques allowing for uni- or bilateral antegrade selective cerebral perfusion (SCP). Unilateral SCP using direct cannulation of the axillary artery (**A**). Bilateral SCP via perfusion of the axillary artery and the left common carotid artery with a balloon occlusion cannula (**B**). Antegrade bicarotid perfusion with two balloon occlusion cannulas (**C**). Bilateral SCP via the axillary artery using the Trifurcated graft technique by Spielvogel *et al*. [45] (**D**).

carotid artery stenosis, previous stroke or anatomical anomalies, e.g. an incomplete Circle of Willis, are thought to be potentially limiting for unilateral SCP.

Variations in the configuration of the Circle of Willis are also well known and seem to occur in more than 50% of men. Circle deficiencies based on anatomical aspects were thought to be rather rare. However, Merkkola *et al*. [46] discovered missing anterior communicating arteries in 22% and missing left posterior communicating arteries in 46% in their anatomical population. The authors determined an arterial diameter threshold of 0.5 mm—allowing for sufficient collateral circulation—and postulated that in the case of unilateral perfusion via the right axillary artery insufficient left hemispherical perfusion would have resulted in 14% of cases [46]. Another anatomical study of 122 cadavers identified significant anatomical variations—compromising collateral circulation during unilateral SCP—of the Circle of Willis in 42.4% [47]. Therefore, Papantchev *et al*. suggested performing preoperative computed tomography (CT) angiograms to identify high-risk patients in whom bilateral SCP should be considered. Other authors believe that preoperative CT angiography is unnecessary in the clinical setting and is replaceable by several diagnostic modalities, such as functional carotid occlusion test, and use of transcranial Doppler or near-infrared spectroscopy (NIRS) [48]. Papantchev *et al*. most recently introduced a new classification system on anatomical variations of the Circle of Willis—present in 58.6% of 500 examined circles—potentially causing hypoperfusion during unilateral SCP.

Controversially, it has been hypothesized that the Circle of Willis might not be the only pathway for cerebral cross-perfusion and, therefore, it has been concluded that extracranial collateral circulation most likely plays a meaningful role during unilateral SCP in patients with an incomplete Circle of Willis [48]. Insufficient unilateral perfusion during SCP can usually be detected with NIRS—therefore, one strategy some centres execute is to initiate unilateral SCP and switch to bilateral perfusion if NIRS monitoring indicates insufficient oxygen saturation of one hemisphere [49].

Leshnower *et al*. [6] reported a clinical series of 344 hemiarch and 68 total arch replacements using unilateral SCP with a perfusate temperature of 16°C and an average distal arrest of 30 ± 15 min at 26°C, with an overall mortality of 7% and TND and PND neurological deficits of 5.1 and 3.6%, respectively. More recently, Urbanski *et al*. [5] presented the excellent clinical results that his group achieved with unilateral SCP at a perfusate temperature of 28°C and distal HCA at 31.5°C for 34 min with an overall mortality of 1.2%, TND of 2.3%, and PND of 0.9% in a series of 77 total and 270 partial arch replacements and concluded that: 'Systemic mild-to-moderate hypothermia that is adapted to the duration of circulatory arrest is a simple, safe and effective method of organ protection and can be recommended in routine aortic arch surgery with circulatory arrest and cerebral perfusion'.

In 2010, a quality-of-life survey by Krähenbühl *et al*. [50] showed that in the case of prolonged durations of deep HCA (>40 min), the use of bilateral SCP is superior to unilateral SCP with regard to mid-term quality of life. A literature review on aortic arch repair with more than 3500 patients treated with either uni- ($n = 599$) or bilateral ($n = 2949$) cerebral perfusion revealed that bilateral SCP allows for longer durations of cerebral perfusion with equivalent neurological outcome [51]. Therefore, the authors suggested the routine use of bilateral SCP if prolonged durations (>40–50 min) of cerebral perfusion are required [51]. The most recent meta-analysis, including 5400 patients soon to be published by Angeloni *et al*., showed equal overall mortality and PND rates between uni- and bilateral SCP, however, TND rates were significantly higher in the bilateral SCP group.

Despite promising results with the use of unilateral antegrade SCP [5, 6, 45], most surgeons aim for bilateral SCP to ensure bilateral perfusion, particularly when longer operation times are expected [19, 23].

MODERATE HYPOTHERMIA AND SELECTIVE CEREBRAL PERFUSION

The issue of optimal temperature management to avoid neurological complications during arch surgery utilizing SCP remains one of the most controversial topics in aortic surgery these days. Despite the absence of confirmative experimental data for the safety of higher body core temperatures, more and more clinical centres tolerate moderate-to-mild (28–35°C) hypothermic, or even normothermic body core, temperatures during arch repair.

Clinical use of moderate hypothermia

Encouraged by the success of antegrade SCP in routine cases, many surgeons began to progressively aim for higher CPB and SCP perfusate temperatures [52–54]. This change in paradigm towards a more moderate temperature management was driven by the incentive to avoid potential hypothermia-associated complications, shortening the duration of cooling and rewarming on CPB and was another rationale not to be underestimated. Initial clinical results are suggesting that higher degrees of hypothermia allow for sufficient cerebral protection during SCP [23]. However, the adjusted degree of hypothermia during aortic arch surgery should always provide sufficient organ protection of the lower body. This should be a paradigm, a conditio-sine-qua-non or a non-negotiable condition for total arch surgery.

Cook *et al*. [52] reported a trend towards significantly higher incidence of delirium following SCP and profound HCA (<22°C)—in comparison with deep HCA (>22°C). In 2007, the Bologna group published their results of 305 aortic arch operations either with deep-to-profound (<22°C) or deep hypothermia of up to 26° C with an average SCP time of up to 60 min [53]. Interestingly, no differences could be found between both groups with regard to 30-day mortality (12.7 vs 13.8%), PND (3.1 vs 1.7%; $P = 0.72$) and TND (7.9 vs 8.6%) [53]. More recently, Pacini *et al*. [55] reported excellent outcomes of 95 elderly patients (≥75 years) treated with profound antegrade cerebral perfusion of 20°C and lower body circulatory arrest (LBCA) for 24 min at 25°C. Prolonged LBCA (>40 min) and femoral cannulation sites were identified to be significant risk factors for postoperative mortality and neurological complications [55]. Leshnower *et al*. [6] also showed very low neurological complications (PND 3.6% and TND 5.1%) following unilateral SCP at 16°C with a body core temperature of 26°C in more than 400 patients. Panos *et al*. [54] reported a series of 25 patients suffering from acute Type A dissection who were successfully perfused by unilateral SCP via the axillary artery and distal arrest at a rectal temperature of 25–27°C for 40 min. The safety of deep HCA alone for ultra-short durations (<10 min) of distal arrest at 26°C without SCP has been confirmed by various contemporary series since Borst and Griepp developed this concept.

Paraplegia has previously been a virtually unknown complication following aortic arch surgery using SCP and profound HCA. In 2007, Kamiya *et al*. [56] were the first to report on the possible hazard of neurological complications during prolonged LBCA and moderate hypothermia at 28°C. In a subgroup analysis, Kamiya *et al.* found a 6-fold increase in mortality and ischaemic spinal cord injury: their propensity score analysis clearly demonstrated a significantly increased mortality of 27% and paraplegia rate of 18% in 92 patients with SCP and prolonged LBCA of >60 min at a body core temperature of 25–28°C [56]. In comparison, the paraplegia rate in patients operated on during SCP and LBCA (>60 min) at deep hypothermia (20–24°C) was 0% [56].

Despite the clinical evidence that prolonged durations of LBCA bear the risk of neurological complications, particularly permanent spinal cord injury, some propose to aim for even higher temperatures with the incentive of shortened duration of surgery. In 2012, Urbanski *et al*. [5] published their results of a series of 347 patients, using SCP and moderate-to-mild LBCA of up to 31.5°C (range 26.0–35.0°C) for an average duration of 18 min in hemiarch repairs ($n = 270$) and 29 min for total arch replacements ($n = 77$). Postoperatively, 5 of 347 patients required dialysis and only 1 patient suffered from bowel ischaemia; 30-day mortality (0.9%) and neurological complications (PND 2.3% and TND 0.9%) were remarkably low, with no occurrence of paraplegia [5]. However, with regard to these results, the authors suggested the routine use of moderate-to-mild HCA and SCP during aortic arch surgery [5]. More recently, the Emory group retrospectively compared the outcome after elective and emergent hemiarch replacements with SCP for 25 min at deep and moderate temperatures (24.3 vs 28.6°C) [57]: propensity-matched analysis revealed a significantly reduced rate of PND (2.5 vs 7.2%) in the moderate group—there were no significant differences with regard to bleeding, TND or renal failure between the groups [57]. However, their propensity matching did not consider the complexity of arch repair and previous neurological status—risk factors well known to influence the outcome after arch surgery.

In another clinical series by Zierer *et al*. [7], of 245 patients undergoing moderate HCA (30.5°C) and SCP for an average of 38 min, permanent and temporary neurological deficits occurred in 6 and 5%, respectively. Postoperatively, increased levels of lactate, creatinine and liver enzymes were monitored, but no bowel ischaemia or liver failure occurred; however, dialysis-dependent renal failure occurred in 7% of patients [7]. In comparison, a recent clinical series of hemiarch repairs by Lima *et al*. [58] using SCP for 20 min at profound HCA (18°C) resulted in a 30-day mortality of 2.8%; rates for PND (stroke), renal failure and respiratory failure were 0.8 (4.1% in emergent cases), 1.2 and 0.4%, respectively.

Nervous tissue is known to be most susceptible to warm ischaemia. The radical change in temperature management towards moderate-to-mild body core temperatures bears a significant risk of ischaemic spinal cord injury causing a wide spectrum of neurological damage from temporary paraparesis to irreversible permanent paraplegia [19]. Fortunately, the incidence of postoperative neurological and visceral complications following SCP and deep-to-moderate HCA of up to 30 min remains rare; however, lower body ischaemic tolerance at moderate or even mild hypothermia is as yet unknown.

EXPERIMENTAL RESEARCH

Although clear evidence on the limitations of moderate hypothermia during aortic arch surgery has been reported [56], guidelines for the safe use of SCP and LBCA with regard to temperature management are not available due to the lack of expert consensus. Various experimental studies have been undertaken to evaluate the impact of moderate hypothermia on both the viscera and the spinal cord.

Ischaemic tolerance of the spinal cord

In 2003, the Mount Sinai group demonstrated that spinal cord ischaemic tolerance is significantly prolonged when cooling from normothermia to mild hypothermia (32°C) prior to aortic cross-clamping [59]. While cross-clamping during normothermia (36.5°C) was limited to 20 min, mild hypothermia (32°C) remarkably increased the spinal cord ischaemic tolerance to up to 50 min [59]. In comparison, 25 min of normothermia and 60 min of mild hypothermia resulted in paraplegia [59]. Another experimental series utilizing the same porcine model by Halstead *et al*. [20] showed that even 90 min of profound hypothermia (15°C) did not result in any impairment of motor function.

With regard to the clinically reported risks of prolonged LBCA in aortic arch surgery in 2007 [56], the Mount Sinai Group aimed to define spinal cord ischaemic tolerance at moderate body core temperatures in a porcine SCP model. Etz *et al*. [60] used the previous data on spinal cord ischaemic tolerance to generate a logarithmic plot of body core temperature vs SCP time to define a possible safety margin for LBCA at moderate hypothermia of 28°C. Based on these assumptions, an experiment designed to prove that prolonged SCP and LBCA for 90 min is safe—while 120 min at moderate body core temperatures is assumed to result in permanent paraplegia—failed to confirm the safety of this approach for the 90-min group in the majority of animals, with an overall postoperative mortality of 60% and a paraplegia rate of 100% in the remaining animals [60]. Therefore, the initial assumption that 90 min of moderate hypothermia at 28°C in combination with antegrade SCP may be safe for the spinal cord had to be corrected (Fig. 3).

With regard to recent clinical and experimental data, a safe ischaemic interval for the spinal cord can be estimated these days as follows [45, 59, 60]:

(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)

However, more experimental studies are needed to clearly define the spinal cord ischaemic tolerance at higher core temperatures—between 32 and 37°C—progressively proposed to be safe for arch surgery.

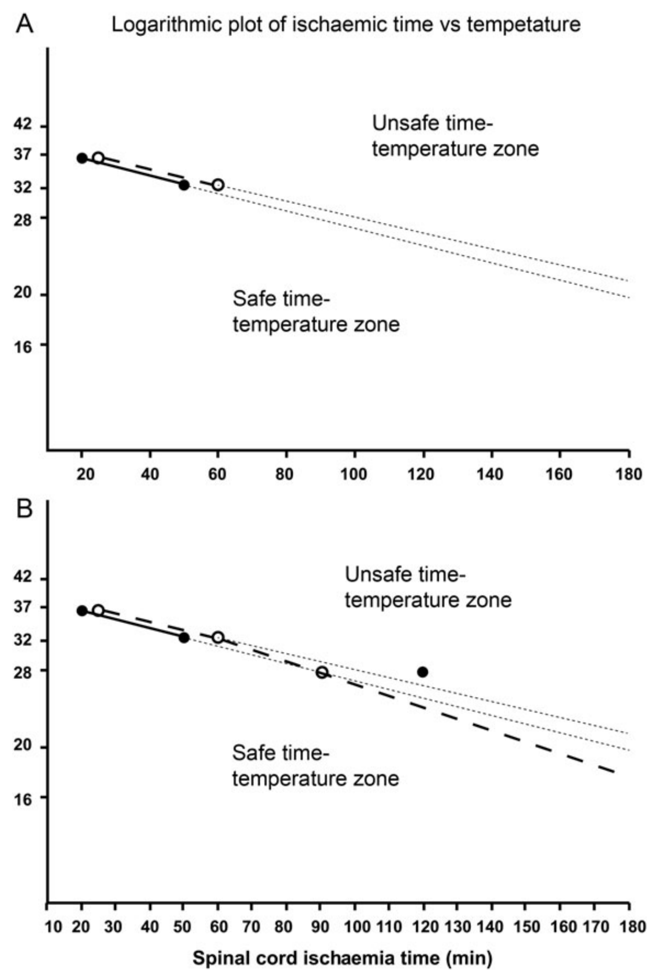

Figure 3: Plot indicating safe (solid line) and unsafe (bold dashed line) time–temperature points following aortic cross-clamping with a straight line extrapolation: aortic cross-clamping was safe for 20 min at 36.5°C and for 50 min at 32.5°C (black circles); unsafe for 25 min at 36.5°C and for 60 min at 32.5°C (open circles). SCP at 28°C was unsafe for 90 and 120 min. The dashed line represents the revised extrapolated border between safe and unsafe time–temperature. The *y* axis is a logarithmic scale for temperature. (Reprinted from Etz *et al*. [60], with permission from Elsevier.)

Ischaemic tolerance of the abdominal viscera

Visceral ischaemic damage during elective aortic arch surgery at deep hypothermic temperatures remained an uncommon event in the past, since the ischaemic tolerance of the abdominal viscera most likely exceeds spinal cord ischaemic tolerance at a given core temperature.

In the experimental series by Etz *et al*. [60], most of the animals died during the first postoperative 24 h due to multiorgan failure or respiratory insufficiency after ischaemic injury. With regard to these results, significant injury to the abdominal viscera appears to occur at 90 min during SCP and LBCA, and 120 min is likely to result in fatal ischaemic multiorgan injury [60]. Khaladj *et al*. [61] compared the impact of 60 min of either moderate (30°C) or profound (20°C) HCA on visceral end-organ function in a porcine model. Higher circulating lactate levels during reperfusion as well as histological evidence of more pronounced oedema formation within the bowel wall in the moderate HCA group (30°C) indicated less-effective organ protection at 30°C than at 20°C after 60 min of HCA [61].

Clinically, it seems that—among the viscera—the kidneys are most sensitive to ischaemia, followed by the liver and the bowel [6, 7]. However, the clinical impact of ischaemic damage to each organ is different and depends on the available treatment options, e.g. acute renal failure vs bowel infarction.

DISTAL PERFUSION

Moderate-to-mild perfusion strategies avoid deeper temperatures and significantly shorten extracorporeal circulation times, but also bear risks for the non-perfused organs of the lower body in case of prolonged operations times, or if unexpected technical problems do occur. The clinical results by Kamiya *et al*. [56] raised serious concerns about the safety of prolonged moderate hypothermic distal circulatory arrest. As the spinal cord and the abdominal viscera may be at risk during higher temperatures, some surgeons implemented additional perfusion strategies for the lower body, including additional distal aortic perfusion.

Minatoya *et al*. [62] compared three groups of patients who underwent aortic arch surgery using bilateral SCP and circulatory arrest temperatures of 20, 25 and 28°C, respectively. Stroke and TND rates were not significantly different between the three groups and no postoperative paraplegia occurred in any group [62]. It is important to note that in the 28°C group, the authors used significantly higher SCP flows of 19 ml/kg/min ($P < 0.0001$) and additional left subclavian artery perfusion for fear of spinal cord ischaemic damage [62]—a strategy in line with the modern collateral network concept of spinal cord arterial supply [60, 63, 64].

However, the perfusion strategy by Minatoya during SCP only covers the cervical to mid-thoracic segments of the spinal cord since no blood flow is provided to the lumbar cord by perfusion of the supraaortic vessels only [60]. It is therefore of utmost importance to have specific knowledge of the spinal cord's collateral supply to ensure sufficient distal perfusion during the operation.

Currently, the classic theory of spinal cord blood supply by the Adamkewicz artery is being challenged by the collateral network concept—which appears to more sufficiently correlate with clinical observations with regard to spinal cord integrity when compromising spinal cord perfusion [64]. This concept is based on the idea that an arterial paraspinous collateral network, mainly fed by the vertebral, segmental (intercostal) and hypogastric arteries (internal iliac arteries), has the ability to increase local blood flow to overcome acute and chronic ischaemic states [63–65]. However, aortic cross-clamping results in acute spinal cord ischaemia—eliminating more than two-thirds of cord perfusion via the aortic segmental and hypogastric arteries—leaving only the vertebral and upper intercostal arteries for spinal cord supply despite (proximal) SCP [60, 63]. This fact was underlined by a recent multicentre study by the European Registry of Endovascular Aortic Repair Complications (EuREC): acute endovascular stent-graft coverage of at least two inflow territories of spinal cord blood supply was significantly associated with spinal cord ischaemia (positive predictive value: 0.75; 95% confidence interval: 0.38–0.75; $P < 0.0001$) [66].

Della Corte *et al*. [67] used thoracoabdominal perfusion during aortic arch surgery in 80 patients—via descending endoluminal cannulation ($n = 62$) or femoral artery cannulation ($n = 18$)—and compared the postoperative outcome with 122 patients with aortic arch operations without additional distal perfusion in 2006. Despite the fact that overall mortality and PND rates did not significantly differ between both groups, data analysis revealed significantly lower incidences of respiratory (18.2 vs 30.5%) and renal (6.5 vs 18.6%) failure as well as shorter durations of mechanical ventilation (18.1 vs 57.9 h), intensive care and hospital stay ($P = 0.02$) in the thoracoabdominal perfusion group [67]. In 2007, Nappi *et al*. [68] published their thoracoabdominal perfusion technique—using a cuffed endotracheal tube for descending aortic perfusion—with no permanent neurological complications in 12 patients at a body core temperature of 26°C. The use of prefabricated prosthetic grafts also allows for distal perfusion once the distal aortic anastomosis has been performed [5, 36] (Fig. 4A and B).

Additional distal perfusion via the femoral artery to avoid lower body ischaemia during aortic arch surgery was already used by De Bakey *et al.* [9] (Fig. 1) and has been shown to be superior to the 'clamp-and-sew' technique during extended thoracoabdominal aneurysm repair [69]. Recently, distal perfusion via the femoral artery has also been successfully used in selective cases during total aortic arch replacement to sustain spinal cord and visceral integrity at moderate hypothermia by more inexperienced teams (Fig. 4C). Moreover, due to proximal aortic cross-clamping, the known disadvantages of retrograde perfusion via the femoral artery, such as stroke in atherosclerotic disease, are unlikely to occur.

Fernandes *et al*. [70] used simultaneous unilateral SCP and distal aortic perfusion via the femoral artery in a young patient with Marfan's syndrome while performing valve-sparing root, ascending aortic and total arch replacement using the elephant trunk technique. Unilateral SCP was administered with a flow rate of 1–3 l/min at 25°C via the right axillary artery, while simultaneous distal lower body perfusion was performed via the femoral artery (1–3 l/min) at a lower body core temperature of 30°C [70]. Aoki and Sangawa [71] successfully used additional perfusion of the lower body via a balloon occlusion catheter during aortic arch repair in an elderly patient at a moderate body core temperature of 28°C for 60 min. Touati *et al.* [72] even performed aortic arch repair at normothermic conditions with unilateral SCP at 70 mmHg, intermitted myocardial perfusion via the coronary sinus and distal femoral perfusion at 50 mmHg in 19 patients. Hospital mortality was 6.8% ($n = 2$) and only 1

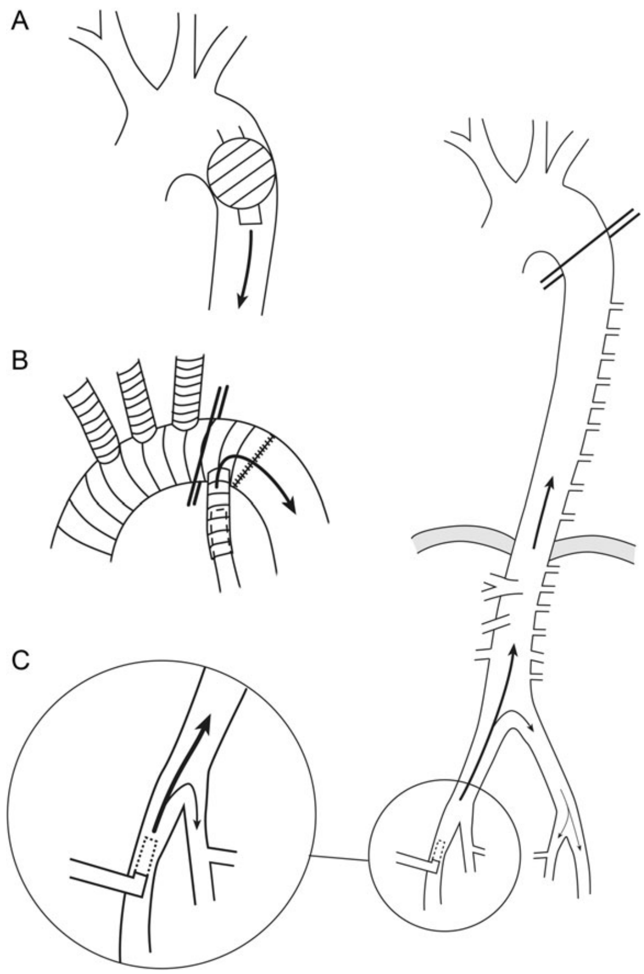

Figure 4: Various techniques of distal aortic perfusion for both visceral and spinal cord protection. Antegrade perfusion of the descending aorta can be achieved with a balloon occlusion cannula (**A**) or after finishing of the distal anastomosis using a prefabricated prosthetic graft as reported by Kazui *et al.* [36] (**B**). Direct retrograde aortic perfusion via the femoral artery (**C**).

patient suffered from neurological sequelae and required prolonged ventilation. No incidence of visceral or spinal cord ischaemia occurred [72]. However, with regard to the above-mentioned clinical and experimental findings, it must be clear to the surgeon utilizing this strategy at normothermia that there is absolutely no room for error [9, 56, 60].

Recent experimental research also confirmed the protective effect of distal aortic perfusion during LBCA at moderate hypothermia. Peterss *et al*. [73] demonstrated in a porcine model that 50 min of low-flow distal aortic perfusion decreased initially elevated lactate levels—after 10 min of moderate LBCA—and only slightly elevated parameters of renal or liver impairment after 60 min at a body core temperature of 30°C.

These results strongly suggest that the use of distal perfusion may reduce the incidence of end-organ complications to the visceral organs and—in particular—the spinal cord, particularly in more extensive and time-consuming aortic arch operations.

DISCUSSION

Antegrade SCP in combination with profound-to-deep HCA has unquestionably been the gold standard and the method of choice for surgery of aortic pathologies involving the transverse arch during the past decade [2, 14, 23, 36].

Currently, there is no definite consensus yet on which approach might be the optimal cannulation site of choice or whether to favour bilateral or unilateral perfusion for SCP. The Emory group recently analysed their experience of 708 patients who had undergone aortic arch surgery since 2004 [57]. Five hundred patients had hemiarch replacement at temperature of 22°C (or higher) with unilateral SCP. Leshnower *et al*. [57] propensity matched (for 19 variables, including history of CVA) 277 patients who had undergone hemiarch replacement at a moderate temperature of 28.6°C with 233 patients who had undergone hemiarch replacement at a deep average temperature of 24.3°C. They found similar operative mortalities for elective and urgent cases, no difference in the incidence of temporary neurological deficits and (interestingly) a similar re-exploration rate for bleeding [57]. However, patients with moderate vs deep temperature management had a significantly lower rate of permanent neurological deficits (2.5 vs 7.2%; $P = 0.01$), which was confirmed by the propensity score (adjusted odds ratio of 0.28; $P = 0.02$). Another clinical study, including 129 patients with unilateral and 162 patients with bilateral perfusion, suggests an advantage for bilateral perfusion with regard to quality of life in cases that require prolonged SCP of >40 min [50]. Malvindi *et al*. [51] also concluded that bilateral SCP may be favourable in cases of prolonged SCP durations (>40–50 min) after comparing several studies on aortic arch surgery, including more than 3500 patients treated with either uni- ($n = 599$) or bilateral ($n = 2949$) SCP. Certainly, an interesting hypothesis to be proven!

There is evidence, however, that bilateral antegrade SCP is currently the best method for cerebral protection, particularly in more complex cases of total arch replacement (>30–40 min), but unilateral SCP may be adequate if circulatory arrest is limited [42].

Several anatomical variations of the Circle of Willis exist that raise concerns whether uniform perfusion of all cerebral territories may be achieved during unilateral SCP [46, 47]. Although special consideration has been given to certain patient groups with an interrupted Circle of Willis, clinically, these variants appear to remain unapparent with no significant advantage for bilateral SCP, suggesting sufficient arterial collateralization [48]. Urbanski *et al*. [49] only reported 1 case in which unilateral SCP was insufficient, requiring conversion to bilateral SCP—clearly less than patho-anatomical studies would suggest, due to a lack of major anatomical anastomoses [46, 47]. Therefore, preoperative individual CT angiography to ensure Circle of Willis patency before performing unilateral SCP seems unnecessary with regard to the neurological outcome of contemporary clinical studies [6, 48].

Nevertheless, the potential risk of nonuniform cerebral perfusion demands adequate monitoring techniques to allow for an early switch to bilateral SCP if required. NIRS is a noninvasive method allowing for continuous monitoring of bihemispherical oxygenation during SCP [42]. However, the NIRS technique only monitors the mixed tissue oxygenation of the motor frontal lobes within close location to the forehead and, therefore, cannot account for complete neuromonitoring during either uni- or bilateral SCP! Transcranial color Doppler (TCD) ultrasound has also been proposed for continuous noninvasive real-time monitoring of CBF during HCA [74]. The possible advantage of this method is that intracerebral arteries are directly monitored, allowing for the optimization of SCP and fast intervention

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by the surgeon and anaesthesiologist if hypo- or hyperperfusion phenomena are detected [74]. The combination of NIRS for regional cerebral oximetry and TCD of the middle cerebral artery mean velocity (VmMCA) has been proposed by Wang *et al.* [75] who found a significant correlation between both parameters in their pilot study of 12 patients; interestingly, only regional cerebral oximetry significantly correlated with pump flow (while off-pump regional cerebral oximetry and VmMCA correlated with antegrade SCP flow). However, further developments to ultimately allow for complete blood flow monitoring during SCP are still required to safely exclude any risk of cerebral malperfusion.

Using SCP and deep HCA, experienced centres achieve excellent results that represent the benchmark against which future concepts of organ protection will have to prove superior [14, 23, 45]. The Kobe group just presented their excellent results with 321 consecutive patients undergoing total arch replacement utilizing antegrade SCP at a minimal tympanic temperature of 20–23°C (tolerating moderate rectal temperatures <30°C); in their landmark analysis, Okada *et al.* [76] reported an overall mortality of 4.4% (1.9% in elective cases) and a permanent neurological deficit of 4.4% (2.8% in elective cases).

Currently, many groups (including not only highly experienced centres of aortic surgery) are progressively moving towards the new perfusion strategy of SCP and more moderate LBCA [77]. This paradigm shift is encouraged—or even driven—by the promising results by aortic specialists who advocate the routine use of moderate-to-mild (28–35°C) hypothermia during aortic arch operations [5–7]. It is supposed—despite the absence of experimental proof suggesting the safety of this new concept—that moderate or even mild distal ischaemia should be safe and effective for a limited period of time (30–60 min) during standard cases of arch reconstruction (e.g. hemiarch replacement) [5, 7, 57]. Moreover, this concept is currently not only used in elective cases, in which it is legitimate to expect a short operation time, but has been proposed for use in the emergency repair of acute aortic dissection [54]. This radical change of temperature management inevitably increases the risk of prolonged distal ischaemia during 'warm' LBCA, and thereby, introduces a new—so far unknown—complication during elective aortic arch repair: ischaemic spinal cord injury.

The temperature relationship for the safe interruption of blood flow has been considered similar for the brain and the spinal cord; however, the absolute times for safe ischaemia for the brain and spinal cord differ because of a 4-fold difference in baseline metabolism at normothermia of 37°C (5 vs 20 min) [13, 59]. Strauch *et al*. [59] showed that even mild hypothermia of 32°C increases total ischaemic tolerance of the spinal cord during LBCA. However, as shown by Etz *et al*. [60] in their recent experimental study, moderate hypothermia (28°C) clearly has safety limits with regard to spinal cord integrity during prolonged distal circulatory arrest. It is of great importance to point out that all animals, even the non-paraplegic, had suffered from significant ischaemic spinal cord damage as confirmed by histological examination at the end of their experiment [60]. Postoperative spinal cord damage involving the posterior horns—carrying most of the sensory and ascending pathways—could easily be missed clinically since loss of motor function, e.g. paraplegia, is not necessarily coexistent.

Visceral ischaemic damage during elective aortic arch surgery with distal arrest at deep hypothermia body has also been an uncommon complication in the past. However, since warmer body core temperatures are increasingly tolerated during aortic arch surgery, the risk of ischaemic damage to the abdominal viscera most likely increases as well. Experimental studies suggest that prolonged durations of LBCA certainly affect visceral organ integrity and will ultimately result in severe ischaemic damage, e.g. bowel infarction or even multiorgan failure [60, 61]. Patel *et al*. [78] identified prolonged LBCA times (36.6 ± 15.6 min)—along with age and increased creatinine levels—to be an independent predictor of long-term mortality in their series of 721 open aortic arch reconstructions.

Additional distal perfusion during aortic arch surgery has been shown to reduce the incidence of end-organ complications, even in more extensive and time-consuming procedures [67, 68]. Haldenwang *et al*. [79] experimentally compared mesenteric perfusion during antegrade SCP (10 ml/kg/min) at 28°C and low-flow (20 ml/kg/min) distal aortic perfusion vs distal arrest in a piglet model. They revealed diminished—but considerable—mesenteric regional blood flow during low-flow distal perfusion (jejunum: 47% and colon: 68% of baseline perfusion) vs virtually no mesenteric perfusion (5% of baseline) during distal arrest [79]. Their experimental findings contrast the clinical practice of Numata *et al*. [80], suggesting that antegrade SCP with moderate hypothermia offers sufficient distal organ perfusion in their series of 84 patients.

The risk of retrograde distal perfusion via the femoral artery (embolism by air or debris) seems to be low, as long as retrograde perfusion is used only during distal cross-clamping or balloon catheter occlusion [70–72]. However, Pacini *et al.* [55], in their recent series of 95 elderly patients undergoing antegrade SCP and moderate HCA, revealed femoral cannulation for CPB to be a predictor of serious adverse events (mortality and neurological injury). A finding that may be linked to the fact that the incidence of cerebrovascular disease seems to be higher in the elderly with aortic arch rather than with isolated ascending aortic pathologies.

Outcome after extensive arch surgery depends on various details, including individualized technical considerations (e.g. cannulation site, perfusion technique, temperature management), longstanding surgical experience and, of course, a well-trained interdisciplinary team to allow for excellent perioperative patient care—which might often be underestimated.

The excellent results recently published—claiming a new concept of moderate or even mild hypothermia as the only neuroprotective approach—might encourage others to adopt this technique despite experimental evidence. Optimal temperature management may differ with regard to the preferred surgical technique or the level of surgical experience (aortic vs non-aortic centres). Comparing the results of different study groups—with different temperature management—remains difficult. A hasty recommendation at this time to routinely use moderate-to-mild hypothermia (range between 28 and 35°C) in combination with SCP for aortic arch surgery—particularly at non-aortic centres—might be dangerous, particularly since high body core temperatures are difficult to correct during the procedure—in the case of unpredicted technical problems—and only a minority of experienced centres so far uses additional distal perfusion.

Further refinements with regard to intraoperative (real-time) monitoring and management of the brain, the spinal cord and the visceral organs are strongly required to continuously improve outcome after aortic arch surgery independent from the preferred surgical strategy.

Figure 5: Intraoperative monitoring of the paravertebral collateral network (CN) using near-infrared spectroscopy (NIRS) to detect possible malperfusion of the spinal cord. The optical sensors are placed on the left and on the right side at the thoracic (1 + 2) and the lumbar level (3 + 4), respectively. A possible drop of oxygen saturation below the (preoperative) baseline indicates decreased perfusion of the paravertebral CN that can be antagonized by increasing the systemic mean arterial pressure (MAP) and/or by draining cerebral fluid via the routinely placed CSF drainage at the lumbar level (asterisk).

Most recently, we began using the potential of NIRS to measure regional tissue oxygenation during aortic surgery at the Leipzig Heart Center to monitor and potentially detect related spinal cord ischaemia in selected cases. With regard to the clinical and experimental studies by the Mount Sinai group [60], perioperative monitoring at our institution was upgraded using NIRS optodes, bilaterally placed on the patient's paravertebral muscles at the thoracic and the lumbar levels, to monitor the paravertebral muscle oxygenation (paravertebral collateral network) as an indirect parameter for sufficient arterial collateral network supply to the spinal cord [63, 65] (Fig. 5). This approach can easily be used in any setting of aortic surgery, particularly during thoracoabdominal repair, to allow for early detection of spinal cord malperfusion: a possible drop of oxygen saturation below the (preoperative) baseline indicates a decreased perfusion of the paravertebral collateral network, which may be addressed by increasing the systemic mean arterial pressure.

It also remains of great importance to always look 'outside the box', particularly with regard to new treatment options proposed by experts in other fields. In brief, there is a contradictory trend in emergency medicine to progressively apply therapeutic hypothermia for neuroprotection in patients who suffered from global cerebral ischaemia after cardiac arrest—a fact that should remind us all to recall the neuroprotective potential of systemic hypothermia.

A uniform terminology of the four different stages of hypothermia to allow for better comparison, as well as a clear definition of the extent of the procedure to be undertaken (e.g. hemiarch/moderate hypothermia; total arch/deep hypothermia), appears essential to facilitate discussion among experts in the field. An expert consensus—led by the scientific cardiac societies—on optimal temperature management during aortic arch repair is strongly required to lead the way into in the future of modern aortic arch surgery—without putting patients unnecessarily at risk.

Conflict of interest: none declared.

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