Review

Hypothermic circulatory arrest during ascending and aortic arch surgery: the theoretical impact of different cerebral perfusion techniques and other methods of cerebral protection

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Summary

Operations on the thoracic aorta using hypothermic circulatory arrest are still associated with significant morbidity and mortality due to neurological complications. During the last decades, different cerebral protection techniques have been introduced into clinical practice to reduce the incidence of such complications. Furthermore clinical as well as basic researches have been performed to improve the outcome after these operations. Currently different cerebral perfusion methods are in clinical use and the superiority of one or the other method is a matter of controversial discussion. This review has been undertaken to evaluate the theoretical impact of these different methods of cerebral protection. Based on the experience of the authors the pros and cons are discussed with clinical and experimental reports from the literature.

Keywords: Cerebral protection; Selective cerebral perfusion; Aortic surgery; Hypothermic circulatory arrest; Retrograde cerebral perfusion

1. Introduction

Worldwide, the outcome of patients after thoracic aortic surgery has improved considerably compared with results reported one or two decades ago. These improved surgical outcomes are probably chiefly a result of increasing expertise in dealing with different pathologies of the thoracic aorta. Nevertheless, as has been shown in several reports, surgery of the thoracic aorta is still associated with significant morbidity and mortality due to neurological complications. The incidence of neurological complications following aortic surgery has ranged in the literature from 5 to 70%. It is difficult to know which factors have a decisive impact on neurological outcome. Are they primarily patient- or pathology-related? Do they depend on the surgical technique? What influence does the method of detection have on the incidence of complications found?

As described by Ergin from the Mount Sinai group, there are mainly two different types of neurological injury which have to be distinguished [1]. First is frank stroke, which is usually the result of an embolic event, and is often not unexpected, since severe calcification is a frequent observation in patients with aneurysms of the aortic arch. Typical neurological symptoms depend on the location and size of the defect as well as on individual patient variables. Imaging can be via diagnostic MRI tomography as early as 12 to 18 h after the event; CT scanning is usually positive after 24 to 48 h. Clinically, transient strokes have to be distinguished from permanent insults, with their dismal consequences for the patient.

The second type of neurological injury occurring as a consequence of aortic surgery has been termed ‘temporary neurological dysfunction’ (TND) and is a reflection of imperfect brain protection during circulatory arrest, as demonstrated by a highly significant correlation between
TND and duration of hypothermic circulatory arrest (HCA) in several studies [1,2]. Typical clinical symptoms are confusion, agitation, delirium, prolonged obtundation, and Parkinson-like symptoms. Reich and coworkers were able to demonstrate that this syndrome—often classified as fleeting harmless cognitive dysfunction—is still present after 3 and 6 months, respectively [3]. Depending on its severity, TND may only be detectable with a sensitive neurocognitive test battery; it is usually not accompanied by radiological imaging abnormalities. Nevertheless, cognitive dysfunction may have an adverse impact on the quality of life of the patient, who expects to regain his/her preoperative neurological status.

Based on the findings of Ergin and coworkers these major types of neuronal injury can be thought of as independent of one another, and their incidence potentially reducible via different approaches. However, in a more recent study including 717 patients who had HCA, it could be demonstrated that there was a correlation between very long HCA times and the incidence of strokes [2], suggesting a potential interaction between the two mechanisms of injury. Prolonged ischemic periods, especially in the penumbra, may aggravate the size of an embolic defect, causing clinical neurological symptoms which might be averted if effective reperfusion after only a short interval of interrupted cerebral blood flow is possible during surgery. Similar observations had been published earlier by Svensson and coworkers [4], who showed that HCA intervals longer than 40 min were associated with significantly higher stroke rates than shorter intervals. Since these neurological complications have major implications not only for our patients but also for society at large, there has been increasing interest in neuroprotection strategies during thoracic aortic surgery on the part of a number of investigators.

Based on clinical experience, surgical strategies have changed over time. Currently most surgeons try to avoid HCA and favor methods providing blood flow to the organ most sensitive to ischemia: the central nervous system [5–7]. The question whether to perfuse the cerebrum retrograde or antegrade is still somewhat of a matter of controversy, since clinical and experimental data offer conflicting results [8,9]. Furthermore, different cannulation techniques have been used to reduce the incidence of embolic events. Finally the idea of preischemic drug treatment is another appealing approach with potential to improve neurological outcome. Intraoperative neuromonitoring has become an additional tool in this type of surgery, but interpretation of the results is complicated by a number of factors.

The present manuscript is a synopsis of experimental and clinical data regarding various cerebral protection strategies during thoracic aortic surgery. Pros and cons are discussed, and the rationale for the specific technique used in our institution is provided.

2. Hypothermic circulatory arrest

The introduction of HCA as an operative tool more than 30 years ago still serves as the basis for the surgical treatment of complex pathologies of the thoracic aorta. It allows the surgeon to excise the distal clamp site, completely view the aortic anatomy in a bloodless field, and perform a distal anastomosis without leaving any clamp-compromised tissue. The primary concept is based on the idea of reducing the brain’s activity—and therefore energy demand—to a minimum. Since enzymatic intracellular reactions are temperature-related, cooling reduces the requirements for oxygen delivery and the release of potentially detrimental excitatory neurotransmitters such as glutamate [10]. The pH and adenosine tri-phosphate stores can also be better preserved at cooler temperatures.

The question whether alpha-stat or pH-stat management during cooling should be used is still a matter of controversy. pH-Stat management seems to abolish autoregulation, causing high flow due to vasoplegia and loss of resistance. With this ‘luxury perfusion’, the risk of cerebral edema increases, as does the risk of embolic events. On the other hand, this technique may provide more thorough and sustained cooling of the tissues. Alpha-stat management preserves autoregulation even at low temperatures, mitigates acidosis, and may avoid an accumulation of body fluid. In reviewing the literature, it seems that there is no consensus regarding whether to use alpha or pH-stat in adults. Differences in anatomy, especially aorto-pulmonary collaterals, may favor the use of pH-stat management in infants with congenital heart disease, further complicating understanding of this complex issue [11].

There remain, in addition, other unsettled questions. What temperature should be achieved before the extracorporeal circulation can be stopped? And what is the anticipated ‘safe’ interval for a repair without neurological complications? The answers to these questions differ substantially among institutions. Electroencephalographic silence, the suppression of somatosensory evoked potentials (SSEPs), high jugular venous bulb saturations, defined cooling intervals, and achievement of specific core temperatures are methods used clinically to define what is thought to be adequate metabolic suppression prior to circulatory arrest. Methylprednisolone and barbiturates are frequently administered before HCA, and the head may be cooled with ice to prevent rewarming of the central nervous system. Whether pre-oxygenation or preconditioning may be beneficial for the brain—as shown for the myocardium—is still unknown. With current methods, most clinicians consider 35–40 min of HCA at 20 °C as relatively safe, but there is increasing evidence that the interval is probably a lot shorter.

Mezrow and coworkers [12] were able to demonstrate in a canine model that oxygen consumption became progressively lower as temperature was reduced. Cooling to 18 °C—the standard temperature in many institutions—was still
associated with 34% of baseline oxygen consumption; further cooling to 13 °C reduced metabolism to 20% of baseline, and profound cooling to 8 °C reduced it to 5% of control. In a clinical study in humans, McCullough and coworkers [13] showed that the predicted safe duration of HCA at 13 °C is only 29 min, and concluded that shorter intervals and lower temperatures than those currently used may be necessary to provide adequate cerebral protection during HCA. Reich et al. [14] have confirmed that patients with arrest times longer than 25 min have a higher incidence of TND, and a greater degree of cognitive dysfunction on psychometric testing. On the other hand, profound hypothermia is associated with prolonged cardiopulmonary bypass (CPB) times, activation of the inflammatory system, and coagulation disorders predisposing to postoperative bleeding. These observations prompted a search for adjunctive techniques to gain the luxury of time for a complete repair and yet avoid the negative side effects of profound cooling.

3. Retrograde cerebral perfusion

In 1990, Ueda and associates [15] proposed the use of retrograde cerebral perfusion (RCP)—a technique originally used to treat major air embolism during CPB [16]—as an adjunct to HCA for the repair of aortic arch pathologies. The theory is that retrograde flow is established via the superior vena cava (SVC) during deep hypothermia to increase the cerebral ischemic tolerance and prolong the clinically safe duration of HCA by providing metabolic support, removing potentially toxic metabolites, and preventing rewarming of the cerebrum during the period without antegrade flow. In the years which followed, this popular technique became routine in many institutions despite a lack of adequate experimental data. Basically, there are two different techniques by which RCP is implemented. First is its use as an adjunct to HCA, with continuous retrograde perfusion as long as the brain is expected to be ischemic. Several authors claim excellent clinical results [8,17] with this technique. Other groups prefer to flush the cerebral circulation briefly, particularly in cases in which the risk of embolic events is judged to be high [2]. Some discussion has centered on whether the inferior vena cava should be clamped during retrograde perfusion to avoid volume loss via collaterals, at the cost of brain perfusion.

Independent of the specific technique, the pathophysiological background of RCP is still not well understood, and many open questions remain. Which parts of the cerebrum can be reached via this approach, and does the magnitude of flow allow RCP to be of any nutritive value? Is shunting an issue? Does cerebral edema occur, and is it a problem? To answer these questions, different groups started to study the effects of RCP in the laboratory. Unfortunately, differences in anatomy and neurophysiology of different species made interpretation of the findings difficult. Furthermore, significant differences in the presence and reliability of outcome measures complicate interpretation.

In 1995, Boekestans and Flameng [18] showed in a primate model that only a small amount of blood reaches the brain, but the majority is shunted to the lower body via veno-venous pathways. This finding was confirmed by Ehrlich et al. [9] in a porcine model using colored microspheres, as well as by Filgueiras et al. [19], who showed, by using magnet resonance spectroscopy, that only a small amount of blood reaches the brain: not enough to prevent metabolic evidence of ischemia. Katz and coworkers [20] showed, in a study in rabbits using radioactive tracers, that retrograde flow through the SVC reaches the cerebral venous system but not the capillaries.

In contrast to these findings, Ono [21] was able to demonstrate in five patients who underwent aortic arch surgery that fluorescein injected into the SVC cannula could be seen in retinal capillaries and arterioles. Since the retina is part of the brain, they concluded that RCP provides blood flow for the cerebrum. Additional studies comparing the regional cerebral blood flow during RCP and CPB with different methods (e.g. hydrogen clearance and laser Doppler methods) have demonstrated that about 20–60% of hypothermic CPB flow can be achieved via retrograde pathways. An excellent overview with a detailed description of the specific techniques was published by Reich and coworkers in 2001 [22].

But, in addition to the question of flow, there is still controversy concerning the necessary pressure to achieve adequate perfusion. It appears that the effectiveness of RCP increases if the vena cava is cross-clamped and potential decompression avoided. Clinically, the venous pressure is controlled via either a central venous catheter in the SVC or a jugular bulb catheter, and the flow is adjusted to maintain pressure in the range of 20–25 mmHg. Since it was demonstrated by deBrux and coworkers [23] in a cadaver study in humans that the jugular vein may contain valves, higher perfusion pressures—up to 40 mmHg—have been used. But high perfusion pressures and flow rates can cause accumulation of total body fluid and cerebral edema, especially if RCP is prolonged [24–26]. Since it has been shown in a chronic porcine model that higher intracranial pressures during reperfusion are associated with poorer neurological outcome, this approach seems questionable [27]. In a clinical setup, Higami and coworkers [28] were able to demonstrate a continuous fall in cerebrovascular oxygen saturation with time during RCP, eventually reaching a critically low level, whereas with selective cerebral perfusion (SCP) there were no time limitations. We speculate that this may be a reflection of increasing tissue edema during RCP, with an adverse influence on oxygen exchange in the capillary bed.

But how can we explain the excellent clinical results demonstrated by some investigators using RCP? It seems that the effectiveness of RCP can mainly be attributed to
more thorough and sustained cooling, especially if circula-
tory arrest temperatures are relatively high. Experimental
data by Anttila and coworkers [29] in a chronic porcine
model seem to confirm this assumption.

Putting all data together, the mechanism of cerebral
protection using RCP remains elusive. A large number of
experimental and clinical studies demonstrate a spectrum of
beneficial, neutral, and detrimental effects of RCP [22]. It
appears that the usefulness of this adjunct is based more on
faith than on reliable experimental and clinical data. It
therefore seems prudent to look for an alternative rather than
depending on a technique which seems to have a very small
margin for providing benefit without inducing harm.

4. Selective antegrade cerebral perfusion

In 1957, de Bakey and colleagues were the first to apply
the technique of selective antegrade cerebral perfusion to
resect an aneurysm of the aortic arch. Despite the successful
treatment of this patient, results in the following years were
disappointing. Therefore, the repair of these lesions was
essentially abandoned until 1975, when Griepp et al. [30]
showed that aortic arch repair is possible using HCA alone.
But with the recognition of the limitations of HCA, as well
as increasing expertise in the field of aortic surgery in the
past few decades, it became apparent that adjunctive
techniques might offer the luxury of time for a more
complete repair or aortic arch lesions along with a decreased
incidence of neurological complications. Since the real
benefit of RCP is not uniformly accepted (see above), this
perception opened the door for the revival of the antegrade
selective perfusion technique.

The concept of antegrade perfusion is an appealing one,
since it is definitely more physiologic than any ‘no flow’ or
retrograde approach. Basically, this technique is used in
combination with deep or profound hypothermia and
perfusion of one or more supraaortic vessels. In recent
years, the trend has gone from deep temperatures—as
advocated by the Mount Sinai group—toward higher
temperatures: up to 25 °C with selective cold (15 °C) [5,6]
or even moderate (25 °C) [31] perfusion of the brain. The
avoidance of deep core temperatures offers the advantage of
shorter CPB times, a reduction of coagulation disorders, and
a reduced accumulation of inflammatory parameters, but
includes theoretically the risk of spinal cord ischemic injury.
Our own experience with this technique includes more than
250 cases (without acute type A dissection) without any
paraplegia even when the cerebral protection time has
exceeded 60 min. In this cohort hospital mortality was 4.5%,
6% had permanent neurological dysfunction, and 7%
suffered from TND.

Over time, there have been some modifications in how
cerebral perfusion has been implemented technically. The
group from Nieuwegein [32] showed, in a series of 106
patients who underwent surgery on the thoracic aorta using
HCA and antegrade cerebral perfusion, that hospital
mortality was significantly affected by the choice of
technique used for antegrade cerebral perfusion. Whereas
unilateral cerebral perfusion was associated with higher
mortality rates, bilateral antegrade SCP had a protective
effect (odds ratio 0.08). Since aortic patients frequently
suffer from a high amount of comorbidity, including carotid
artery stenosis or an incomplete circle of Willis, these
results are not unexpected. Bachet and coworkers [5] use
pursue string sutures in the innominate and left carotid artery
with proximal clamping before initiation of cold (10–12 °C)
SCP. We feel, as do others [7], that this procedure
potentially increases the risk of embolic strokes due to
manipulation of diseased and calcified vessels.

We prefer to use special catheters—which were orig-
inally designed for retrograde cardioplegia—(RCSP MR 20,
15F, Medtronic, Minneapolis, MN, USA) and introduce
them during a 3–5 min interval of HCA under visual control
via the opened aortic arch into the innominate and left
carotid arteries. After meticulous de-airing, perfusion is
started with a flow rate of 10 ml/kg/min and is adjusted to
maintain the pressure in the right radial artery between 40
and 60 mmHg. If backflow via the left subclavian artery
compromises the surgical field, the subclavian artery is
occluded with a Fogarty catheter. This technique offers, in
our opinion, a relatively uncompromised surgical field,
.avoids clamp injuries of the arteries, and minimizes the risk
of microembolic events. The proper location of the balloon
catheters can easily be controlled by non-invasive spec-
troscopy (INVOS®, Somanetics, Troy, MI, USA). The
continuous observation of pump flow, pressure, and oxygen
saturation allows the anesthesiologist to treat the con-
sequences of vagaries of vasomotor tone which frequently
occur during SCP.

Griep and associates have routinely used another
elegant technique to avoid direct cannulation of vessels
[2]. Under profound HCA, Griep creates an island
including all three head vessels, and attaches the graft. An
arterial inflow cannula is now inserted, the distal end of the
graft clamped and flow initiated. Usually this procedure
takes 10 min of HCA but allows completely resection of all
diseased tissue. The proximal and distal anastomoses are
constructed using a second piece of graft. The arch
reconstruction is then completed by an end-to-side graft-
to-graft anastomosis of the arch and ascending aortic grafts.
This is usually accomplished during a second brief (5–10
min) interval of HCA. The appeal of this technique for
complete repair must be weighed against its requirement for
deep hypothermia during the two periods of HCA. One
advantage is that this technique can easily be combined with
right axillary cannulation which is now routinely used
in many aortic centers (see Chapter 5, Cannulation
techniques).

Kazui and coworkers [33] reported 220 consecutive
patients who underwent total arch replacement, using
initially ‘homemade’ then commercially available arch
branched grafts, with a phenomemonally low overall inhospital mortality of 12.7% and overall neurological dysfunction rate of 9.3%. He used hypothermic extracorporeal circulation and antegrade SCP, and found that SCP time had no significant influence on in-hospital mortality and neurological outcome. This fact is especially remarkable since total circulatory arrest times were on average >45 min, and SCP time frequently approached almost 90 min.

The Mount Sinai experience, in a non-randomized, retrospective study [2], revealed that TND rates after prolonged periods of ACP were significantly lower than with RCP or HCA alone. In the largest series to date, DiEusanio and coworkers [34] included 413 patients who were operated on the thoracic aorta using selective antegrade cerebral perfusion: they were able to demonstrate that even cerebral perfusion times of more than 90 min were not associated with a higher incidence of neurological complications; urgent status and a recent history of central neurological events were important risk factors for outcome. Okita and coworkers [35] compared two groups of patients who underwent total arch replacement with deep HCA, one with adjunctive RCP, and the other with ACP. Despite the fact that the duration of the operation, total bypass time, and aortic cross-clamp time as well as ‘cerebral protection times’ were significantly longer in the HCA + ACP group, the incidence of transient brain dysfunction was significantly higher in the HCA + RCP group.

From these data, the technique of ACP, in experienced hands, seems to be an extremely useful adjunct to HCA alone. On the other hand, surgeons have to be aware, that any manipulation of the aortic arch can cause dislodgement of debris especially if the arch is severely calcified. These embolizations are often associated with a typical picture in the CT scan that we termed ‘Swiss cheese’ damage due to a number of small circumspect lesions in the periphery of the brain.

5. Cannulation techniques

The problem of embolic events and cerebral malperfusion due to acute aortic dissections also has to be discussed in the context of a number of possible cannulation techniques. In elective surgery of the ascending aorta or the aortic arch due to aneurysms, the standard cannulation with one cannula in the ascending aorta and one in the right atrium is generally accepted. Nevertheless, loose material like atheroma, clots, and calcifications are potential sources of potentially catastrophic embolic strokes. Preoperative CT scanning, manual palpation of the aorta or even epiaortic ultrasound might help, in such cases, to find a plaque-free area in the aorta for cannulation. Specially designed catheters to harvest emboli during the cannulation procedure have been shown to be valuable, but have not achieved general acceptance for routine use [36].

In the case of reoperations or acute emergencies (e.g. dissection), the femoral vessels are still the most common site for arterio-venous cannulation since they are easy to access and serve as a safe backup during opening of the chest. On the other hand, arteriosclerosis is usually a generalized problem, frequently involving the femoral and iliac arteries as well as the abdominal aorta. Even if femoral cannulation is possible, reversing the blood flow from antegrade to retrograde may shear off embolic material which can cause dissection or embolic showers.

One alternative is the cannulation of the right axillary artery as described initially by the University of Massachusetts group from Worcester and the Cleveland Clinic group in 1995 [37]. The axillary arteries are usually not calcified, and they are rarely involved in aortic dissection [38]. Surgically the axillary artery is challenging to access, which is probably because most surgeons are not used to using it. Care has to be taken if the lateral segment of the artery is used, since it is surrounded by the brachial plexus roots and lymphatic tissue. Special angled cannulas simplify introduction, and keep the cannulation site out of the surgical field. As an alternative, the graft interposition technique can be used, and this method for axillary artery cannulation is favored by some surgeons [39]. In general, the complication rate of axillary artery cannulation is low: thrombosis, brachial plexus injury, and intraoperative malperfusion have only rarely been seen.

Svensson [40] recommends subclavian artery side-graft antegrade perfusion with occlusion of the innominate and left common carotid arteries with balloon catheters and observed a favorable outcome.

A straightforward approach is used at the author’s institution. The ascending aorta is cannulated under echocardiographic guidance in the majority of cases. This allows identification of the false and true lumen and can be helpful in determining the correct cannulation site. If malperfusion is encountered (as assessed by pressure monitoring in both radial arteries), the pump is stopped, the arch opened, and an incision made in the membrane between the true and false lumen of the dissection. Thereafter, CPB is reestablished, and the repair completed under moderate HCA with selective cold antegrade cerebral perfusion. Our experience includes currently more than 50 patients who were operated for acute type A dissection using the direct ascending cannulation technique and we experienced only two cases where the problem of malperfusion was encountered. Both were treated as described without neurological consequences or other complications. In none of the cases we decided to use an alternative cannulation site due to the echocardiographic findings.

6. Pre-ischemic drug treatment

Cessation or severe reduction of blood flow results in almost instantaneous biochemical and functional deficits in
the brain, which become rapidly irreversible unless blood flow is promptly restored. The ischemia time that is tolerated by the brain depends on the tissue concentrations of primary and secondary energy stores and the rate of energy consumption, which, in turn, depends on temperature (see above), the degree of functional activity, and the presence of anesthetics or other drugs. From animal studies, it is well known that there is also a major difference between the ischemic vulnerability of different regions of the brain. As an example, the CA1 sector of the hippocampus may suffer irreversible injury after 5 min of normothermic ischemia, whereas other nerve cell populations survive even 1 h of ischemia [41]. This depends in parts on the metabolic rates of the specific cells and is sometimes determined by the anatomical blood supply. From clinical studies, we know that prolonged periods of HCA can cause cognitive dysfunction with anatomical correlates in the limbic system of the organism.

The pathophysiology of cerebral ischemia is further complicated by the fact that the severity of cell injury is modulated by numerous indirect or secondary consequences of the primary trauma, with some of the damage possibly occurring during reperfusion. Understanding the mechanism of neuronal death associated with CPB, hypothermia, and circulatory arrest may provide valuable information for possible drug intervention to prolong the ‘safe’ time for ischemia during operations on the thoracic aorta. Baumgartner and his group from Johns Hopkins University [10] have demonstrated that excitotoxicity is likely to be one important mechanism of neuronal cell injury and death after hypoxia and ischemia. The use of specific glutamate receptor blockers in the dog model has a markedly favorable influence on outcome after HCA, but the toxicity of these drugs makes their use in humans impossible.

In a number of other animal studies, it has been demonstrated that cerebral ischemia causes neuronal injury via apoptotic pathways as well as by necrosis [10,42]. In a chronic porcine model, we were able to demonstrate histologically that significant neuronal apoptosis occurs as a consequence of HCA, but other patterns of cell injury and death seem to predominate. Deeper temperature as well as pretreatment with cyclosporine, an apoptosis inhibitor, reduced the number of dead neurons, but not as a consequence of interrupting apoptotic pathways. Since cyclosporine is also an antinflammatory agent, this may play a role in the ability of cyclosporine to mitigate neuronal cell death after HCA and to improve neurophysiological recovery [43]. Studies in a chronic porcine model of HCA at various temperatures show that there is a neuroprotective effect of a combination of cooler temperatures and preischemic treatment with cyclosporine [44].

In conclusion, there are a number of interesting drugs available that may interfere in the injury cycle after HCA (e.g. Na-blockers, Ca-blockers, glutamate inhibitors, radical scavengers, and NO pathway inhibitors). In principal, any drug that has had a promising neuroprotective effect in post-ischemic animal testing but has failed to show an effect in Phase III trials after stroke should be re-tested to see whether it might be effective if used before an ischemic insult. The problem of preventing ischemic injury during aortic surgery has the advantage of a defined period of ischemia and the potential of direct drug delivery to the vulnerable tissue prior to the ischemic insult. Due to the large number of possible drugs—each able to interfere with a specific event in the ischemic cascade—it seems even more promising to explore treatments with a carefully selected combination of neuroprotective agents than with each drug alone. Examples of synergistic effects with this kind of approach have been demonstrated in experimental stroke research.

In a very recent publication by Allen and coworkers [45], the idea of a ‘whole body reperfusate’ using compounds known to be protective for different organ systems is another new and appealing concept for trying to improve neurological outcome after aortic surgery [46].

7. Intraoperative neuromonitoring

Neurophysiological monitoring during thoracic aortic surgery using HCA became increasingly popular in the last decade. Besides its value during an ongoing operation, the collection of data in combination with outcome analysis might help to improve or change surgical strategies. Continuous recording of electroencephalograms (EEGs) as well as SSEPs is now routine in most neurosurgical units. The use of neuromonitoring in cardiothoracic surgery is in part hampered by the fact that hypothermia has an impact on the sensitivity of neurophysiological measures, so they cannot be used during deep hypothermia. On the other hand, some surgeons have found this an asset, and use disappearance of the EEG to determine the optimal level of hypothermia before they stop the extracorporeal circulation. Problems with interpretation of EEG monitoring occur because of variability of the disappearance of detectable potentials within a wide range of temperatures (18–24 °C) in different individuals, and also its sensitivity to environmental noise. Therefore, the value of the EEG as an isolated method for ascertaining whether cerebral protection is adequate is questionable. Furthermore, nonsynaptic metabolic activity may persist even when the EEG is isoelectric.

On the other hand, the EEG may provide valuable information for those groups [31] which are using relative high blood temperatures during SCP. Furthermore, EEG seems to be a good tool for detecting electrophysiological recovery in the early postoperative period. In several animal studies, we were able to demonstrate a close correlation between early EEG recovery during reperfusion after HCA and improved postoperative neurobehavioral outcome in those animals, although we failed to find consistent data during cooling. Interestingly, we also found a strong correlation between lower intracranial pressure
during reperfusion and the probability of an early EEG recovery [27].

Monitoring of SSEPs is generally easier than EEG since electric noise does not play such a substantial role. It is generally less influenced by anesthetic drugs, and it remains detectable as long as cortical activity can be encountered. From clinical experience, SSEPs seem especially valuable during surgery on the descending or thoracoabdominal aorta (which is not subject of the present synopsis) but muscle evoked potentials (MEPs) may be even more sensitive for detection of spinal cord injury.

In a fine review by Edmonds, there was clear evidence that multi-modality neuromonitoring for cardiac surgery is safe, clinically beneficial, and cost-effective and provides substantial benefits for the patients outcome [47].

8. Conclusions

There are a substantial number of potential methods to protect the brain during surgery on the thoracic aorta. Many of them differ only in detail, and proof of superiority of one over another method may be difficult to demonstrate. From the surgeon’s point of view, there are basically three techniques in clinical use and the question must be raised as to which offers the best protection for the brain. With little question, the basis for all the techniques remains the protection afforded by hypothermia. Despite this fact, the tendency seems to be toward higher temperatures, and away from profound hypothermia, despite its unquestionable protection afforded by hypothermia. Despite this fact, the tendency seems to be toward higher temperatures, and away from profound hypothermia, despite its unquestionable benefits with regard to metabolic suppression.

Instead, perfusion methods to protect the organ most sensitive to ischemia and hypoxia—the brain—have become routine. After some initial enthusiasm for the use of RCP, we have the impression that this method has lost its popularity, although there are still a number of well-regarded surgeons who rely upon it for cerebral protection. From a pathophysiological perspective, and after reviewing the experimental literature, there is—in our opinion—no doubt that ‘antegrade’ perfusion is superior to ‘retrograde’ perfusion. For this reason, the authors abandoned the use of RCP 5 years ago, and rely exclusively on ACP in all patients in whom a period of interruption of normal cerebral perfusion is anticipated, even if it does not exceed 10 min. In return, we avoid deep cooling and stop the heart–lung machine after reaching 26 °C. Brain perfusion, as mentioned, is always started with cold blood, and perfusion pressure is maintained between 40 and 60 mmHg. For neuromonitoring, we use non-invasive spectroscopy, EEG and SSEP recordings. To determine the optimal temperature and flow conditions (pulsatile, non-pulsatile, pH-stat vs alpha-stat, etc.) during ACP, we are currently working in an animal model to validate techniques which are currently, in our opinion, based only on empirical observations.

We believe that potentially neuroprotective, non-toxic drugs will be available in the future and may improve the tolerance of the central nervous system for ischemia or prolonged periods of non-physiological flow. These approaches have to be tested in clinically relevant animal models of extracorporeal circulation. Furthermore, basic research is necessary to gain deeper insight into the pathophysiology of cerebral ischemia.

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