Review Article

Intraoperative care for aortic surgery using circulatory arrest

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Abstract: The total circulatory arrest (CA) is necessary to achieve optimal surgical conditions in certain aortic pathologies, especially in those affecting the ascending aorta and aortic arch. During this procedure it is necessary to protect all the organs of ischemia, especially those of the central nervous system and for this purpose several strategies have been developed. The first and most important protective method is systemic hypothermia. The degree of hypothermia and the route of application have been evolving and currently tend to use moderate hypothermia (MH) (20.1–28 ℃) associated with unilateral or bilateral selective cerebral perfusion methods. In this way the neurological results are better, the interval of security is greater and the times of extracorporeal circulation are smaller. Even so, it is necessary to take into account that there is the possibility of ischemia in the lower part of the body, especially of the abdominal viscera and the spinal cord, therefore the time of circulatory stop should be limited and not to exceed 80 minutes. Evidence of possible neurological drug protection is very weak and only mannitol, magnesium, and statins can produce some benefit. Inhalational anesthetics and some intravenous seem to have advantages, but more studies would be needed to test their long-term benefit. Other important parameters to be monitored during these procedures are blood glucose, anemia and coagulation disorders and acid-base balance. The recommended monitoring is common in complex cardiovascular procedures and it is of special importance the neurological monitoring that can be performed with several techniques, although currently the most used are Bispectral Index (BIS) and Near-Infrared Spectroscopy (NIRS). It is also essential to monitor the temperature routinely at the nasopharyngeal and bladder level and it is important to control coagulation with rotational thromboelastometry (ROTEM).

Keywords: Aortic arch syndromes; circulatory arrest (CA) deep hypothermia (DH) induced; neuroprotection; cerebrovascular circulation; intraoperative neurophysiological monitoring

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Introduction

Ascending aortic and/or aortic arch surgery is a complex procedure that usually requires a circulatory arrest (CA) to achieve a surgical field that is free of cannulas and clamps. During this period there is an important risk of ischemia of all organs, especially of the central nervous system. The International Aortic Arch Surgery Study Group has published a system of organic dysfunction grading to avoid duplication of overlapping results and to limit fluctuating classifications of negative outcomes among institutions by providing standardized definitions (1).

The first measure used to reduce the risk of ischemia was systemic hypothermia. Subsequently, selective cerebral perfusion methods were used to increase the CA safety time.

Initially hypothermia was produced by external cooling and was first applied by Lewis and Taufic in 1953 for the

Table 1 Indications of total CA

Indications	Surgery
Cardiovascular surgery	Surgery on aortic arch
	Complex congenital surgery
	Pulmonary thromboendarterectomy
	Repair of thoracic aortic aneurysms
Neurosurgery	Brain aneurysms
	Arteriovenous malformations
Other	Tumors with invasion of V. Cava

CA, circulatory arrest.

correction of a CIA in a 5-year-old girl, with surface cooling and with a 5-minute stop.

The development of cardiopulmonary bypass (CPB) has allowed to manage blood temperature and obtain hypothermia more quickly and accurately to reduce perfusion flows until we reach temporary CA. In 1975 Griepp *et al.* (2) published the first series of aortic arch operations using profound hypothermic CA and in 1986 Guilmet *et al.* in Europe and Kazui in Japan, successfully introduced selective cerebral perfusion, which allowed the use of warmer temperatures and shorter CPB times.

Other adjuvant measures are possible pharmacological protection, acid-base management and glycemic control.

The main use of CA is in cardiac surgery, especially in surgery on ascending aorta and aortic arch and in congenital heart disease in children. However, there are also other indications (*Table 1*).

The safe duration of CA is controversial and will depend on the hypothermia achieved and the concomitant use of cerebral perfusion.

The main pathophysiological aspects involved in cerebral ischemia-reperfusion are the consumption of adenosine triphosphate (ATP), the excitotoxic action of glutamate, the alterations of ionic homeostasis and the formation of oxygen free radicals. Measures that disrupt this cascade of events will theoretically have neuroprotective potential. However, a second pathway of neuronal death by apoptosis has been found, where mitochondria plays a major role and a third pathway due to necroptosis or programmed necrosis that does not depend on caspases. All this would explain that some measures that seem effective may have no long-term impact, because what they do is delay neuronal death.

Hypothermia

Hypothermia acts by decreasing intracellular enzyme activity and cerebral metabolism rate for O_2 ($CMRO_2$), thereby improving the balance between supply and demand for oxygen. For each degree of temperature decrease the $CMRO_2$ decreases an average of 6–7%, so at 25 ℃ the $CMRO_2$ decreases to 37% and 15 ℃ to 15% of the basal. Cerebral blood flow (CBF) is also reduced in a linear fashion as opposed to the decrease in the $CMRO_2$ that accelerates below 20 ℃ (3).

In addition, hypothermia could also have protective effects by other mechanisms, such as decreased release of excitatory neurotransmitters such as glutamate or increased release of inhibitory neurotransmitters such as gamma-aminobutyric acid, in addition to suppressing intracellular calcium intake and decrease the production of oxygen free radicals (4) attenuating the ischemia-reperfusion syndrome and an overregulation of protective genes may be possible (5).

The arterial pathway of CPB, through which hypothermia can be induced in aortic arch surgery, can be established through different arteries, but the most used are the femoral artery and especially the right axillary artery.

This artery provides several benefits such as the possibility of using it for cerebral perfusion anterograde, eliminating the risk of retrograde embolization from the descending aorta, reduces the risk of retrograde dissection, directs the flow to true light by decompressing false light, there is less chance of malposition and hypoperfusion, and it is also an artery that is usually free from atherosclerotic plaques (6).

It is recommended to cannulate the axillary artery through a prosthetic graft previously anastomosed to the artery because it prevents damage to the arterial wall especially in the case of small caliber arteries (7,8).

In any case, there is no clear evidence of the superiority of the axillary artery to the femoral artery, and the choice will depend on the clinical circumstances of the patient and the surgeon's preferences (9,10).

The type of hypothermia for aortic surgery has been defined in a consensus document (9) as described in *Table 2* and serves as a frame of reference.

The degree of hypothermia and the technique used has been varying over time. CA was initially made with profound hypothermia (PH) or deep hypothermia (DH) as the only protection. *Table 3* shows the theoretical safety intervals calculated with a ratio of metabolic rates at 2 temperatures 10 ℃ apart (Q10) of 2.3 (11).

However, even at 14 ℃ there are between 14% and 22%

Table 2 Consensus on hypothermia classifications in aortic arch surgery

Category	Nasopharyngeal temperature (℃)
PH	≤14
DH	14, 1–20
MH	20, 1–28
Mild hypothermia	28, 1–34

PH, profound hypothermia; DH, deep hypothermia; MH, moderate hypothermia.

Table 3 Calculated safe intervals for interruption of brain perfusion at various temperatures

Temperature (℃)	Cerebral metabolic rate (% of baseline)	Calculated safe duration of HCA (min)
37	100	5
30	56 [52–60]	9 [8–10]
25	37 [33–24]	14 [12-15]
20	24 [21–29]	21 [17–24]
15	16 [13–20]	31 [25–38]
10	11 [8–14]	45 [36–62]

Data are means with 95% confidence intervals (CI).

of patients that do not reach the electrical silence (12). One study found that in order to achieve cerebral electrical inactivity in >95% of patients it was needed to lower the temperature to 12.7 ℃ (13).

Subsequently, retrograde cerebral perfusion (RCP) methods were developed through the superior vena cava, to increase the safety time of DH.

More recently, anterograde selective cerebral perfusion methods were started using supra-aortic trunks that allowed the use of moderate hypothermia (MH).

PH (<14 ℃): the use of PH did not provide significant advantages, since the decrease in metabolism is small in relation to DH (14) and in addition to all the problems associated with DH, it should be added that it greatly lengthens the CPB time, causes a loss of brain self-regulation and promotes immunosuppression. For these reasons and for the marginal benefit obtained the PH is rarely used today (15).

DH (14.1–20 ℃): most patients achieve electrical silence with this temperature range (12).

Using only this technique, without selective cerebral perfusion support, acceptable results were obtained (16), provided that the CA did not last more than 20 or 30 minutes, because after 40 minutes of CA the ACV increased significantly (17), even transient neurological dysfunctions have been reported below 30 minutes (18).

DH also has a number of drawbacks such as high CPB required for cooling and warming of the blood, cerebral microvascular endothelial dysfunction, edema formation, coagulopathy and impaired function of many organs including kidneys, brain, vascular smooth muscle, intestinal mucosa, alveolar epithelium, liver or pancreas (19).

The use of HD as the only protective measure was associated with the occurrence of permanent neurological lesions in 3% to 12% of the patients, renal dysfunction in 5% to 14%, pulmonary insufficiency in 5% to 39% and heart failure in 7% to 34%.

MH (20.1–28 ℃): since the use of selective cerebral perfusion methods, more moderate systemic temperatures were started, reducing the CPB time used for cooling and rewarming, and decreasing complications associated with DH previously explained.

Mild hypothermia (28.1–34 ℃): some groups have used even warmer temperatures (30±2 ℃) with good results in both mortality, neurological deficits and organ failure (20,21).

DH vs. moderate

Due to the disadvantages associated with DH, the use of this technique has been decreasing and CA is currently chosen at higher temperatures associated with specific brain protection strategies because it is the organ most sensitive to ischemia.

In studies comparing DH with MH with selective cerebral perfusion for elective aortic surgery, the latter technique was proven to be safe, with better morbidity and mortality. Thus in a meta-analysis by Tian *et al.* (22) no differences were found in mortality and temporal neurological dysfunctions, but if an increase of strokes in DH. Halkos *et al.* (23) and Tsai *et al.* (24) in each study found a significant decrease in mortality with MH. Immer *et al.* (25) found that there was an improvement in the quality of life when using cerebral perfusion and warmer temperatures. For his part Vallabhajosyula *et al.* (26), Milewski *et al.* (27) and Leshnower *et al.* (28) did not find significant differences in mortality or neurological alterations between the two techniques, although the first author describes a significant reduction of transfusions with MH and a significantly lower cardiopulmonary bypass (CBP) time.

Table 4 Calculated safe intervals for interruption of spinal cord perfusion at various temperaturas

Temperature (°C)	Safe duration (min)
37	20
32	50
28	75
20	120

Another important aspect when using more moderate temperatures is the possibility of insufficient protection of the lower part of the body during CA, especially of the spinal cord and abdominal visceras.

In 2007 Kamiya published a greater tendency towards the appearance of paraplegia with MH in the subgroup of patients with CA over 60 minutes (29). Similar data had already been found in experimental animal studies where it was found that at 28 ℃ there were up to 60% paraplegia when the PCT was greater than 90 minutes (30).

Table 4 shows the safe times of interruption of the medullary vascularization at different temperatures and calculated according to a Q10 of 2.2 that is almost identical to the cerebral one (11), in fact the DH was used as a method of spinal protection in thoracoabdominal aneurysm surgery (31).

In recent studies, no significant differences were found in the incidence of renal failure or biomarkers of visceral dysfunction between the two cooling techniques as long as the PCT does not exceed 60 minutes (32,33).

External local cooling

The external cooling of the head is performed generally by surrounding the head with icepacks and is recommended in most protocols. It is an inexpensive and easy to apply method and its theoretical advantage is that it would prevent the transmission of heat by conduction or radiation from hottest objects or tissues. It could also decrease the increase of temperature during the CA because despite the electrical silence can persist a certain degree of metabolic activity and would also lower the temperature gradient between the brain and the operating room environment by preventing brain warming. This situation is important when homogenous tissue cooling has not been achieved before CA, as probably it occurs in some patients (34).

However, there are authors (35) who consider this measure to be of little use, because the skull is a poor conductor of thermal energy and when HM is used with CA the gradient between cerebral and environmental temperature is lower and therefore this measure has less sense. It may also interfere with the placement and operation of sensors used in neurological monitoring.

Management of acid-base balance during hypothermia

Hypothermia increases the solubility of CO_2 in plasma and therefore decreases its partial pressure, although the overall content is the same.

If the pH is determined, when pCO_2 is corrected to the actual temperature during hypothermia, it is called pH-stat, whereas the non-correction according to temperature is called α-stat.

The α-stat management has a number of advantages such as maintaining cerebral autoregulation and cellular enzyme activity (36) as well as the coupling between CBF and cerebral metabolic oxygen consumption ($CMRO_2$) and is usually the strategy used during the CPB.

The pH-stat implies hypercapnia, with the consequent increase of CBF which can increase the emboligena load and provoke edema.

However, this cerebral vasodilatation can favor the homogeneity of the cerebral cooling, therefore some authors (36,37) recommend using the pH-stat during the cooling period and α-stat in the rest of the CPB including the rewarming. However, there is no strong evidence to recommend a strategy over another.

Temperature management

Following the recommendations of The Society of Thoracic Surgeons, The Society of Cardiovascular Anesthesiologists, and The American Society of Extracorporeal Technology (38) cooling should be performed gradually by maintaining a temperature gradient between the arterial outlet and the oxygenator venous inlet <10 ℃ to avoid the generation of gaseous embolism. Also during the rewarming, a gradient of T <10 ℃ must be maintained until the out-flow temperature reaches 30 ℃ where it should be lowered to <4 ℃.

The oxygenator outlet temperature should not exceed 37 ℃ to prevent cerebral hyperthermia.

Some authors recommend a cold reperfusion prior to rewarming for at least 10 minutes, especially when DH was used for less than 40 minutes because it appears to reduce neurological events (39).

Selective cerebral perfusion

It is mandatory for MH and optional on DH.

RCP

It was developed in the 80's and involves reversing the circulatory flow, perfusing oxygenated blood to the brain through the superior vena cava and providing flows between 300 and 500 mL/min with pressures of 25 to 35 mmHg. RCP allows a deep and homogeneous cooling of the brain as well as washing solid particles, air bubbles and metabolites, thereby decreasing acidosis in the ischemic brain (36). Associated with DH has allowed to reduce mortality, stroke (40,41) and delirium significantly with respect to the use of isolated DH (42-44).

The main disadvantage is the risk of cerebral edema due to flow or high perfusion pressures

Antegrade cerebral perfusion (ACP)

ACP consists of delivering oxygenated blood to the brain via the arterial route. It can be unilateral through the right axillary artery, subclavian or innominate or bilateral artery with direct cannulation of the supraaortic trunks.

A flow rate of 6 to 10 mL/kg/min and a perfusion pressure of between 40 and 60 mmHg in the right radial artery or 60 to 70 mmHg in the carotid artery is usually used.

At these pressures and at temperatures above 25 ℃, brain self-regulation is usually maintained.

In a meta-analysis where the DH alone was compared with the DH associated with APC, a mortality reduction was aimed at the latter technique, in order to have longer CPB. On the other hand, there were no significant differences in neurological alterations (45).

Retrograde versus ACP

ACP appears to be superior to RCP because it is more physiological with homogeneous distribution of CBF and allows to maintain MH instead of HD. The RCP satisfies only 10% to 20% of the normal perfusion due to the existence of venous shunts, although it may be sufficient to satisfy the demands in case of DH (46). In fact, the beneficial effect of RCP is probably due to maintenance of cerebral hypothermia rather than to metabolic support (47).

The main drawback of ACP is the possibility of cerebral embolisms, by arterial manipulation

Currently ACP is the most commonly used technique for aortic surgery in most hospitals (23,48,49), for its good results (50), and it can increase the safety time to more than 80 minutes (51). It is also described in a propensity matched analysis a reduction of neurological complications and a tendency to lower mortality at 30 days with ACP (52).

However in a meta-analysis of 7,023 patients comparing both types of perfusions, there are no significant differences in permanent neurological dysfunction, stroke or mortality, and the ACP only is superior in the reduction of temporal neurological dysfunction (53).

Based on all these findings, some authors have suggested that RCP can be reserved for cases in which the supra-aortic trunks can not be manipulated by large embolic risk (36).

Unilateral vs. bilateral ACP

The controversy derives from the fact that unilateral ACP may be insufficient in case of carotid stenosis, previous stroke or anatomical abnormalities in the Willis polygon. The bilateral ACP is somewhat more technically difficult and requires more manipulation of the supra-aortic trunks with which the embolic risk is greater.

Studies comparing both perfusions have mixed results. In some publications, a lesser but not significant incidence of stroke with unilateral perfusion has been described (54). However, in a meta-analysis of 5,100 patients (55), no significant differences were found, and in another 6,788 patients (56) the longer CA they were associated with an increase in mortality when the perfusion was unilateral.

The use of one type or another of anterograde perfusion probably depends on the characteristics of each patient, the protocols of each hospital and the existence of asymmetries in regional cerebral oxygen saturation ($SrcO_2$), or electroencephalography (EEG) at start. However, if a CA greater than 40 or 50 minutes is predicted, bilateral perfusion is recommended (57).

Methods of pharmacological cerebral protection

Many drugs have been used for their potential protective capacity such as halogen anesthetics, anti-inflammatories or antioxidants. Frequently the results of experimental studies in the laboratory are promising, however, in prospective, randomized, and controlled studies (36) there is very little evidence of the benefits of its clinical application in humans

Most inhalation anesthetics have neuroprotective

properties, by reducing the excitotoxicity as demonstrated by laboratory studies with Isoflurane and Sevoflurane; but at the clinical level this benefit was not demonstrated, especially in the long term (58).

In vitro Xenon reduced the cortical lesion induced by N-Methyl-D-Aspartate receptors (NMDA) or oxygen deprivation in mice (59).

Barbiturates were considered to be the standard protective drug, and they appear to reduce apoptosis in the laboratory, however, there are serious doubts about their true efficacy (60-62), since although they may provide modest neuroprotection, they do not appear superior to others anesthetics and are potentially less effective when associated with hypothermia. However, according to a survey conducted in Europe in 450 centers, it was found that in 60% of the cases are still used (63).

Propofol appears to be neuroprotective in focal and global ischemia models, perhaps because of its antioxidant and anti-inflammatory properties, but as with other anesthetics, clinical efficacy has yet to be demonstrated (64).

Etomidate does not seem to provide any benefit, it can even worsen ischemic injury.

NMDA inhibitors such as ketamine appear to have some protective effect on focal ischemia although published results on its effect in patients after cardiac surgery are contradictory (47,65).

Lidocaine has been used in continuous infusion, but its use is not currently recommended, and may even increase cognitive dysfunction in diabetics (66).

Corticosteroids have been frequently used because of their demonstrated anti-inflammatory effect, however this does not mean that they have a neuroprotective effect, in fact no beneficial effects have been found in ischemic or hemorrhagic stroke or in cardiac surgery (67,68).

Calcium antagonists have also shown no benefit in these procedures.

Magnesium acts by inhibiting glutamate at the NMDA receptor level, reducing intracellular calcium concentrations. A possible benefit was demonstrated in cardiac surgery (69,70) and ischemic stroke (71), although there is also some study with contrary results (72).

Mannitol appears to have a certain antiapoptotic effect in addition to the osmotic and free radical scavenging effect.

The beneficial effects of mannitol, barbiturates and steroids in type A aneurysm surgery in 2,137 patients were examined in the GERAADA database (60) and no neuroprotective effects of any drug could be ascertained; only mannitol was associated with a decrease in mortality after surgery although it may have been due to its effects on other organs.

In a recent review (73) where a large number of studies were analyzed, only statins and magnesium sulfate reduce the incidence of neurological deficits and no pharmacological treatment reduced mortality.

Hyperglycemia

It can worsen neurological lesions by different mechanisms such as increased lactic acidosis tissue, increasing the tissue availability of excitatory amino acids, favoring inflammation and oxidative stress and injuring the cerebral microcirculation.

In addition, it must be taken into account that during CPB it is usual to suffer hyperglycemia even in non-diabetic patients. *The Society of Thoracic Surgeons* (74) published guidelines for the perioperative control of glycaemia in cardiac surgery, recommending glycemic levels <180 mg/dL, with insulin I.V. in intermittent bolus or better in continuous perfusion, monitoring blood glucose every 30 to 50 minutes. However, intensive treatment with insulin to maintain normoglycemia was shown to increase episodes of hypoglycemia and mortality (75), so it seems reasonable to maintain levels between 140 and 180 mg/dL.

Coagulation

In CA with hypothermia there are multiple coagulation alterations, as those associated with the CPB itself as a decrease in the production of thrombin, consumption of coagulation factors, decrease in the number and malfunction of platelets, fibrinogen deficiency, hyperfibrinolysis and residual effects of heparin, we must add those caused by hypothermia that also causes platelet dysfunction and prolongs prothrombin time and activated partial thromboplastin time. Even in aortic dissections, consumption of coagulation factors in the preoperative period has been reported (76).

For these reasons, all these procedures consume a large amount of blood products for hemostasis.

It is often necessary to replenish clotting factors that can be done with fresh frozen plasma (FFP), prothrombin factor concentrate (PFC) or recombinant factor VII.

The use of FFP is associated with risk of fluid overload and infections, whereas PFC and FVII are associated with a higher risk of thrombosis. In a retrospective study it was shown that with the use of PFC there was less blood

loss although it did not result in less transfusion or lower mortality at 30 days and also described a higher incidence of acute renal failure (77), unlike another study where no significant differences were found between the two strategies in the incidence of renal failure that required methods of extrarenal clearance (78).

The use of fibrinogen may be necessary to achieve levels >200 mg/dL which are considered acceptable. The contribution of fibrinogen with FFP is small, so a very large volume of transfusion would be required. The most reasonable alternatives are the use of cryoprecipitates or fibrinogen concentrates.

When the fibrinogen concentrates are used in CA with DH as first-line therapy produce both an increase in fibrinogen levels (79) and a reduction in transfusions (80).

Platelet transfusion is also usually required because platelet dysfunction and hemodilution thrombocytopenia occur during CPB, there is downregulation of IIB/IIIA receptors and mechanical damage, and hypothermia has deleterious effects on platelet function that do not revert immediately after rewarming.

Platelets interact with fibrinogen and transfusion of fibrinogen may be necessary before platelets.

Antifibrinolytic drugs such as lysine analogues have been shown to reduce bleeding and transfusions (81,82) and are present in most protocols; in any case the doses used vary widely according to the centers.

Renal failure and aortic thrombosis have been reported with the use of ε-aminocaproic acid (83).

Monitoring

Usual monitoring will be used following the standards of the American Society of Anesthesiologists, including a pulmonary artery catheter in high risk patients and transesophageal echography (TEE). In addition, in these procedures, neurological and temperature monitoring is important.

It is convenient to monitor blood pressure in both radial arteries, especially if ACP is used through the right axillary artery, which is the most common, since in this case the left radial artery can be used during CPB and right radial artery during ACP (84).

The TEE is very useful for assessing cardiac function, aortic morphology, blood volume, the existence of intracardiac air and surgical repair, in case of aortic dissection the TEE will help us to identify the presence of a dissection flap, the extent of dissection, can allow us to differentiate true from false light and the presence of thrombus in false light. It also allows us to diagnose accompanying injuries such as aortic insufficiency, pericardial effusion and coronary dissection

The ascending aorta can be seen in mid-esophageal planes, short and long axes, and the aortic arch in the upper esophageal plane in short and long axis. However, the superior third of the ascending aorta and proximal part of the arch can not be accurately visualized due to the interposition of the left bronchus. Likewise, TEE is not a good technique for seeing supra-aortic trunks, although there are some alternative projections that improve vision (84).

Neurological monitoring

It should be multimodal and may include brain function monitors such as the EEG or Bispectral Index (BIS), somatosensory evoked potentials (SEPs) and oxygenation-flow monitors and brain metabolism such as transcranial Doppler (TCD), oxygen saturation in the jugular venous sinus (SjO_2) and near-infrared spectroscopy (NIRS).

Currently NIRS and BIS are the most used, because they are non-invasive, unlike SjO_2, are less complex and require less apparatus than the EEG and SEPs and less subjective than the TCD.

EEG was the main neurological monitoring used in aortic arch surgery with DH to assess electrical activity as a marker of the metabolic suppression produced by hypothermia (85), so that the degree of cooling is marked by electrical silence.

It was verified that the cerebral electrical activity during the cooling follows predictable patterns, although with wide margins (12). Thus, with nasopharyngeal temperatures between 21.5 and 34.2 ℃ (mean 29.6±3 ℃) many patients develop periodic unilateral or bilateral discharge and wave amplitude. With greater cooling there is a gradual decrease in continuity until the appearance of a burst suppression pattern between 15.7 and 33 ℃ (mean 24.4±4 ℃). Finally, with increasing cooling, there is a progression towards complete electrical inactivity between 12.5 and 27.2 ℃ (mean 17.8±4 ℃).

During warming there is a progressive normalization of the EEG but at somewhat different temperatures than during cooling (86).

When using MH with selective ACP the role of the EEG is less established. In these cases CA is usually between 20 and 28 ℃ and at these temperatures the vast majority of patients have some electrical brain activity. In these cases the EEG can

be useful to assess asymmetries or a sudden drop in electrical activity that does not improve with cerebral perfusion and may indicate the performance of other measures such as bilateral ACP or resort to greater cooling (85).

The SEPs have also been used during hypothermic CA. Cortical, subcortical, and peripheral responses may be used during cooling because their suppression should occur prior to CA. The first to disappear is cortical responses, followed by subcortical and peripheral responses (85).

SjO_2 can be measured invasively with a sensor inserted into the jugular vein. SjO_2 increases as $CMRO_2$ decreases. Maximum metabolic suppression is achieved with saturations above 95%.

TCD is a cheap, non-invasive technique that allows detecting changes in real time, especially embolisms and CBF descents usually during ACP (86). Its main drawbacks are that it requires training and experience, it is dependent operator, it is not easily reproducible and it can be difficult to get a suitable signal.

BIS will serve as a monitor of anesthetic depth and is also useful for controlling brain activity during cooling and rewarming.

With hypothermia the value of BIS decreases, often in a biphasic manner (87) and the suppression rate increases. The range of values varies widely among patients, but usually with temperatures <18 ℃ the BIS is 0.

Its usefulness in case of hypothermia would be to identify traces of suppression or electrical silence.

The bilateral BIS adds new variables and one of them is the matrix of spectral density where the frequencies and potential of brain waves are represented with a color chart over time and allows the detection of asymmetries between both hemispheres.

NIRS was developed in the 70's and allows the determination of $SrcO_2$ based on the different absorption properties of light in the near-infrared spectrum of saturated and unsaturated hemoglobin.

Studies done with this monitoring, especially in animals and children, show that $SrcO_2$ increases with the onset of cooling reaching a maximum in most cases after 15 minutes. With the onset of CA there is a decrease in values until circulation is restored and this desaturation correlates with neurohistological damage.

In adults there is less experience, but studies done so far suggest utility (88,89), especially when using selective cerebral perfusion. There are algorithms to increase perfusion flow in case of cerebral desaturation (37) and if it is not enough, bilateral infusion should be used if it was not previously established (90,91). This is why monitoring is used more and more often, although there are some doubts about whether it allows assessing deep brain oxygenation, in fact there seems to be a poor correlation with jugular venous saturation. There are also no data on which threshold or duration of cerebral hypoxia determined by NIRS can be tolerated and compared to the EEG seems to be less sensitive and specific (85).

Temperature monitoring

Several sites have been used for temperature measurement like the tympanum, nasopharynx, esophagus, bladder, rectum and brain. Brain temperature would be the most useful, although difficult.

In a study where hypothermia was used in surgery of cerebral aneurysms (92), it was possible to compare the temperature in the cerebral cortex with other parts of the organism and it was verified that the greatest disparity was with the perfusion temperature and the smallest difference was with the distal esophagus followed by pulmonary artery and nasopharynx. The rectum and bladder were considerably hotter during cooling and colder during warm-up. However, it should be noted that these measurements were performed in closed chest surgeries. In aortic surgery there is loss of heat through the thorax, so in these cases, the temperature closest to the brain is the measurement in the nasopharynx that is also irrigated by branches of the external carotid and therefore comes blood during the ACP.

The thermistor insertion should be through the nares to the level of the midpoint of the zygoma, to a depth of 7 to 10 cm in an adult.

The nasopharynx is a good monitoring site during brain cooling and perfusion, although during warm-up it may underestimate brain temperatura (47), for this reason, it is advisable to control the temperature in two different places and the urinary bladder is often used to measure body temperature although its changes are slower than in the nasopharynx (9).

Coagulation monitoring

Due to the usual coagulation alterations in these procedures, it is interesting to have a point of care that guides our transfusion therapy.

The rotational thromboelastometry (ROTEM) is a point of care assay that examines the viscoelastic properties of

whole blood by dynamically measuring clot firmness during its formation and subsequent fibrinilysis.

The development of algorithms based on these measurements has resulted in reduced bleeding, transfusion of blood products and hospital costs (93).

It seems interesting that the determination of fibrinogen assay of ROTEM (FITBEM A10) during CPB has a good correlation with post-CPB fibrinogen levels (68,94) and this would guide the treatment of early hypofibrinogenemia, which could have repercussions on the reduction of allogeneic transfusions (80).

Future

The use of PCT has decreased because nowadays much aortic arch pathology can be performed with hybrid procedures involving either open or endovascular surgery or completely endovascular procedures that do not require CPB or CA.

The hybrid approach consists of a debranching of supra-aortic trunks with a prosthetic tube from native ascending aorta (type I) or from an aortic graft (type II) and at the same surgical act or in a second time the placement of a stent distal to the outlet of the prosthetic tube and covering the complete arch (95).

Endovascular treatment consists of the placement of a thoracic endoprosthesis with anchorage in the ascending aorta and the insertion of chimneys into supraaortic trunks (96).

Conclusions

The CA is a complex procedure, which requires protective techniques against ischemia. The current trend is using MH with ACP through the right axillary artery. Magnesium, statins, or mannitol may be useful, although more studies would be necessary to recommend its routinary use, because evidence of protection in clinical practice is weak.

It is also important to establish protocols, with the rest of the surgical team and the personal of intensive care, for the monitoring and management of the hemodynamic, respiratory parameters, acid-base balance, glycemia, coagulation and temperatura.

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None.

Footnote

Conflicts of Interest: The authors have no conflicts of interest to declare.

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