Aortic arch surgery using bilateral antegrade selective cerebral perfusion in combination with near-infrared spectroscopy

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Abstract

Objective: Near-infrared spectroscopy (NIRS) complements online monitoring of cerebral oxygenation during aortic arch surgery. Its addition targets at an increase of safety of a complex procedure employing bilateral antegrade cerebral perfusion (BACP) and circulatory arrest under tepid blood temperatures. We report the outcome of NIRS-guided aortic arch surgery using BACP with moderate hypothermic circulatory arrest (MHCA).

Methods: Between December 2006 and December 2008, NIRS was used in 13 patients (mean age: 67.5 ± 11.3 years) undergoing aortic arch repair using BACP combined with MHCA. The diagnosis was atherosclerotic thoracic aneurysms in eight and acute aortic dissection in five patients. Seven patients had a hemi-arch replacement, six underwent frozen stent-graft arch replacement and four patients had concomitant procedures such as coronary artery bypass grafting (CABG) or aortic valve surgery. Our regimen of employing an algorithm for adaptation of perfusion modalities included the threshold of the drop in regional cerebral oxygen saturation \(< 55\%\) and/or a drop in the total oxygen index (TOI) of 15—20\% assessed by the means of NIRS.

Results: The mean MHCA was 35 ± 16 min and lowest bladder temperature was 26 ± 1.2°C. The mean TOI pre-MHCA was 66 ± 6.5\%. Twelve out of 13 patients underwent bilateral perfusion because of unilateral drops below the threshold level of TOI (mean: 44 ± 7.9\%). In three patients, an organic psychosyndrome was observed. No patient developed permanent neurological dysfunction.

Conclusion: NIRS-guided BACP during MHCA allows a safe approach to complex aortic arch surgery. The drop of brain oxygenation values in the contralateral hemisphere during unilateral ACP strongly suggests the routine use of BACP, when circulatory arrest under tepid temperatures is used.

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1. Introduction

Aortic aneurysm surgery involving the aortic arch has seen several changes of the surgical strategy over the last decades. Such complex surgery is still accompanied by a considerable incidence of neurological events. Being of either ischaemic or embolic origin, the latter can be hardly prevented. The questions on how to cannulate and whether to perfuse the brain retrogradely (retrograde cerebral perfusion (RCP)) or antegradely is still a matter of controversy, since publications emerging from different prestigious centres offer conflicting results. Since the real benefit of RCP is not uniformly accepted, this perception opened the door for a broader application of the antegrade selective perfusion technique [1].

Combining modern perfusion strategies including more tepid core temperatures with online neuromonitoring provides the advantage of assessing the adequacy of perfusion in at least some regions of the brain and the possibility of early detection of malperfusion, which can be followed by immediate restoration of adequate perfusion before irreversible damage develops. Near-infrared spectroscopy (NIRS) has been reported as a useful non-invasive monitor to detect cerebral oxygenation states. In order to prevent sustained intra-operative brain oxygen desaturation, which is significantly associated with demonstrable neurological deficiencies, we implemented internationally accepted thresholds for adverse interactions to improve brain oxygen saturation.

Moderate hypothermia for circulatory arrest in combination with bilateral antegrade cerebral perfusion (BACP) is a well-documented technique, which aims at the reduction of postoperative neurological and end-organ sequelae.
Therefore, we and other groups chose the current regimen and we report about the addition of neuromonitoring and the possible impact on further developments in the perfusion strategy.

2. Materials and methods

2.1. Patient population

Between December 2006 and December 2008, online neuromonitoring with NIRS was used in 13 patients undergoing aortic arch repair using antegrade selective cerebral perfusion (SCP) combined with moderate hypothermic circulatory arrest (MHCA). The diagnosis was atherosclerotic aneurysm in eight and acute type-A dissection in five patients. Preoperative characteristics of the patients are summarised in Table 1.

2.2. Surgical techniques

All aneurysms were approached through a median sternotomy. Cardiopulmonary bypass (CPB) was established by the means of right axillary artery (RAxA) perfusion. The RAxA was exposed through a skin incision below the right clavicle. Guided by the thoraco-acromial branch, the artery was dissected. After administration of one-third of the calculated heparin dose, an 8-mm vascular graft (JOTEC GmbH, Hechingen, Germany) was anastomosed end-to-side to the mid-portion of the RAxA at the take-off of the thoraco-acromial branch.

A 20-French (Fr), straight, thin-walled cannula (Medtronic, Minneapolis, MN, USA) was inserted into the graft and connected to the extracorporeal circuit. The remainder of the approach for cannulation was routine, including sternotomy, complete heparinisation with 300 IU kg⁻¹ body weight and cannulation of the right auricular appendage with a double-staged cannula. Patients were cooled to a bladder temperature of 25 °C. As a surrogate for monitoring body temperature, we — similar to other groups [2] — assessed bladder temperature by the means of a thermistor-tipped urinary catheter. Bladder temperature shows the least variations during the period on CPB and seems to be the most accurate method [4]. It gives a closer approximation to pulmonary artery temperature than the nasopharyngeal temperature [4].

After the ascending aorta was clamped, and cardioplegic solution was administered antegrade and/or retrogradely to attain cardiac arrest, the aortic arch was opened and arch vessels were inspected. This was followed by an insertion of a balloon-tipped Prewitt cannula into the left carotid artery. After inflation of the balloon, BACP was initiated. To avoid steal phenomenon the left subclavian artery was blocked by a Fogarty catheter.

Techniques of hemi-arch and frozen stent-graft arch replacement have been described before. Proximal anastomosis was performed while re-warming of the patient was initiated.

2.3. Brain protection

Brain protection using BACP, including RAxA perfusion, was routinely used. Immediately after the induction of HCA preceded by a short discontinuation of the auxiliary perfusion, the innominate artery was clamped, which was followed by restoration of cerebral perfusion via the RAxA and the right vertebral and carotid arteries.

SCP was performed with an ordinary arterial cannula in the graft connected to the RAxA and with a balloon-tipped cannula inserted directly into the left common carotid artery after the aortic arch has been opened. The left subclavian artery was occluded with a Fogarty catheter in all cases. SCP was continued until all branches of the arch were reconstructed. Cerebral perfusion was regulated to maintain the mean pressure at 60 mm Hg. Perfusion pressure measured at the top of the perfusion balloon was considered.

The adequacy of brain oxygenation was monitored by NIRS. By means of this simple manoeuvre, sufficient perfusion of the right hemisphere with partial circulation of the left hemisphere through collateral vessels was provided.

2.4. Neuromonitoring

NIRS is a well-approved, non-invasive, optical-measurement tool for showing the functional activity in the brain. Light of wavelengths between 775 and 850 nm is generated by emitters. After scattering and absorption by tissue, the back-scattered light is detected by two sensors as a function of time, distance and wavelength and they transmit this information to the measurement unit, which is connected to a computerised screen showing real-time graphs. Based on the modified Beer—Lambert law, measurement of oxygenated and deoxygenated haemoglobin, change of total haemoglobin, tissue oxygenation index and tissue haemoglobin index (THI) is possible.

Since the skull is transparent to near-infrared light, a similar approach can be used to measure the intravascular oxyhaemoglobin fraction in a small sample of the cerebral cortex. Therefore, the diodes are attached at the surface of the skin at the right and left frontal cortices.

We used the NIRO 300 (Hamamatsu Phototonics, Hamamatsu, Japan), which uses spatially resolved NIRS as an algorithm, measures a tissue oxygenation index and a THI as
absolute values without the need to know a path-length factor. Tissue oxygenation index represents the tissue saturation and is measured in percent (%), whereas THI is an absolute figure of the total haemoglobin but, due to the factor $k$, is measured in arbitrary units. As it is an absolute value, its changes from one measuring point to another can be measured as a percentage.

Several groups have shown that changes in cerebral oxygenation may be important in brain-injury prevention [5]. It was also showed that NIRS is a diagnostic modality for reflecting cerebral metabolism [6]. However, it has been found that a steep but transient drop in regional oxygen saturation ($rSO_2$) is not related to the occurrence of a neurological event, and this led to the conclusion that brain damage is related to both the extent and the duration of the drop in $rSO_2$ [7]. The regimen of reaction to decreases in cerebral oxygen content follows an algorithm developed a few years ago, which is intended to optimise factors that can affect cerebral oxygen supply/demand. These factors are the position of the vascular cannula, perfusion pressure, arterial oxygen content, partial pressure of carbon dioxide, haemoglobin, cardiac output and the cerebral metabolic rate of oxygen [8]. Our regimen included the threshold of the drop in regional cerebral oxygen saturation <55% and/or a drop of the total oxygen index (TOI) of 15—20% below baseline assessed by means of NIRS. Sample time was every 2 s during the whole surgery.

3. Results

3.1. Patient data

The mean duration of circulatory arrest was 35 ± 16 min. The mean time of CBP was 170 ± 30.6 min with a mean aortic cross-clamp time of 107 ± 37 min. The mean core temperature was 26 ± 1.2 °C (Table 2). Seven patients had a hemi-arch replacement, six underwent frozen stent-graft arch replacement and four out of these 13 patients had concomitant procedures such as CABG and/or aortic valve surgery (Table 3).

3.2. NIRS measurements

After initiation of circulatory arrest and clamping of the brachio-cephalic trunk, unilateral antegrade cerebral perfusion (UACP) was started. After 2 min we observed, generally, a drop in cerebral oxygen saturation to 44 ± 7.9% over the left frontal cortex. Eleven patients had a drop in TOI of 15% and seven of these patients had a fall of 20%. Therefore, in 12 out of 13 (92%) patients, unilateral ACP was switched to BACP with 10 ml min$^{-1}$ kg$^{-1}$ of body weight. A statistically significant increase of cerebral oxygen saturation to 63 ± 5% (TOI; $p < 0.001$) was observed after initiation of BACP (Tables 4 and 5). Changes in cerebral oxygen saturation during UACP and initiation of BACP at the right and left cerebral cortices are shown in Figs. 1 and 2 and also demonstrated by Fig. 3. We did not see any need to increase the flow rate to reach oxygen saturation >55%.

In the single patient with unilateral ACP, a decrease in left-sided cerebral oxygenation saturation from 70% to 60% was observed and stayed at this level during circulatory arrest. Therefore, we did not see the need for institution of BACP.

3.3. Complications and follow-up

One patient, who had been resuscitated preoperatively and was subsequently operated upon due to acute type-A dissection accompanied by dissection in both common carotid arteries, developed a postoperative hypoxic encephalopathy. Eventually, this patient expired.

Transient postoperative neurological delirium occurred in three patients (23%).

Two patients developed a pulmonary infiltration postoperatively and one patient required stenting of the left renal artery due to malperfusion. A deep sternal wound infection followed by vacuum therapy was observed in one patient.

The mean postoperative stay in hospital was 18 ± 9 days with a mean stay in intensive care of 6.7 ± 1.7 days.

Table 3

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<th>Operative procedures.</th>
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<td>Variables</td>
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<tr>
<td>Ascending aorta with hemi-arch (%)</td>
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<td>Ascending aorta with hemi-arch and frozen stent graft (%)</td>
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<td>Associated procedures (%)</td>
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<td>Modified Bentall/according to Cabrol</td>
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<tr>
<td>CABG</td>
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<td>DAVID procedure/AVR</td>
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CABG: coronary bypass grafting; AVR: aortic valve replacement.

Table 4

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<th>Cerebral oxygen saturation.</th>
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<td>Variables</td>
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<tr>
<td>Cerebral oxygen saturation (% ±SD)</td>
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<tr>
<td>Pre-circulatory arrest</td>
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<td>During UACP</td>
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<td>After initiation of BACP</td>
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UACP: unilateral antegrade cerebral perfusion; BACP: bilateral antegrade cerebral perfusion.
The in-hospital mortality was two patients. One patient died after hemi-arch replacement following an acute aortic type-A dissection and preoperative resuscitation as reported above. The other patient died after hemi-arch replacement with aortic valve reconstruction and single arterial revascularisation after experiencing a mesenteric artery embolism.

4. Discussion

There are mainly two different types of neurological injury during surgery of the aortic arch. The one type is 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. 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. These major types of neuronal injury have to be distinguished from each other and the approaches to reduce their incidence have to be planned differently.

However, it has been suggested, that a potential interaction exists between the two mechanisms of injury. Prolonged ischaemic periods 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 or reduced cerebral blood flow, is possible during surgery.

As a matter of fact or fate, the risk of embolisation cannot be excluded. However, in avoiding cerebral ischaemia, we have developed different surgical approaches during the last few decades. One of the approaches is the maintenance of cerebral perfusion during the manoeuvres in the aortic arch area by means of ACP. The concept of antegrade perfusion via the AxA route is an appealing one, since it provides, theoretically, the most physiological concept. One advantage is the fact that the axillary artery is rarely diseased, is seldom involved in the dissection process and can be safely cannulated directly or, as in our case, via a graft with an end-to-side anastomosis. We use this cannulation route routinely in cases of acute dissection, even with extension into the supra-aortic vessels, as well as in emergency situations [9], aortic aneurysms both involving the ascending aorta and the aortic arch and cardiac redo operations. We are aware of the fact that other groups report satisfactory results with different approaches of arterial inflow and cannulation; however, we feel that this route fits best into the concept of selective antegrade brain perfusion and offers the most promising flexibility in adapting flows and pressure to the patients needs assessed by neuromonitoring. AxA cannulation not only avoids aortic manipulation during cannulation but also avoids the retrograde flow of femoral artery cannulation and the resulting ‘sandblasting’ effect of flow in an atherosclerotic aorta [10]. This results in significantly less embolic events if compared to aortic perfusion [11]. This technique is used in combination with deep or moderate hypothermia and perfusion of one or more supra-aortic vessels. In recent years, the trend has gone from deep temperatures (18°C) to more tepid temperatures (28°C).

It has been shown that both UACP and BACP result in a neurological injury rate of <5% [12]. Bilateral perfusion allows longer times of circulatory arrest compared to unilateral perfusion without increasing the rate of permanent neurological disorders [13]. On the other hand, however, during SCP, the risk of cerebral embolism associated with arch-vessel cannulation remains immanent [14] and these manipulations may increase the incidence of stroke [15].
With the present understanding of cerebral cross-perfusion [16], additional neuromonitoring during SCP would seem to be valuable. In our series, cerebral online monitoring was achieved by measurement of regional cerebral saturation with a NIRS, which is easy and fast to perform on all patients and can, therefore, be performed even in emergencies [17]. NIRS provides continuously a non-invasive real-time measurement of cerebral oxygen saturation. Diffuse malperfusion can be avoided only by early detection of malperfusion, followed by immediate restoration of adequate perfusion before irreversible damage develops.

We, along with others, have recognised that the rSO2 promptly drops upon temporary circulatory arrest, and then recovers as circulation resumes in patients undergoing aortic surgery with SCP. In our cohort, we monitored a contralateral drop in cerebral oxygen saturation below 55% in 12 out of 13 patients after commencement of circulatory arrest during UACP. These values came back to normal after additional placement of a cannula in the left carotid artery and initiation of BACP. Thus, selective BACP combined with moderate systemic hypothermia is our method of choice and is reported to be a safe approach compared to deep hypothermia [18].

Our threshold for the need of adaptation between unilateral and bilateral cerebral perfusion was a drop in regional cerebral oxygen saturation below 55%. Reports describe an increase in permanent neurological events when cerebral oxygen saturation drops below 55% for longer than 5 min, and we have not observed any drop below this threshold longer than this period. Similarly, data were reported in cases of carotid endarterectomy with a cut-off level of 54—56.1% [19]. According to other studies, BACP was initiated with 10 ml min⁻¹ kg⁻¹ of body weight [20] and did not have to be increased in any patient. This flow rate seems to be a reference for BACP with cerebral oxygen saturation over 55% at a core temperature between 26 and 28 °C.

It has also been reported that a steep but transient drop in rSO2 is not related to the occurrence of a neurological event, and this led to the conclusion that brain damage is related to both the extent and the duration of the drop in rSO2. These findings can be confirmed by our small series and the observation that the transient, short drops of rSO2 after initiation of SCP unilateral and even after the start of bilateral SCP did not result in any significant neurological damage. The transient drops in rSO2, seen after initiation of SCP and also observed at the right cortex after initiation of unilateral SCP, are probably related to disturbances in cerebral vascular auto-regulation induced by the cold perfusate [21]. After a period of adaptation, the level recovered to near-normal values. The time period during which the levels where low – even <55% – seem to be not long enough to cause damage to the brain tissue.

In different reports, it has been speculated about the differences of low rSO2 values and higher jugular bulb SvO2 values [22]. It should be noted that the magnitude and direction of the difference between rSO2 and SjO2 varied with the absolute value of SjO2. In practical terms, for high values of SjO2, rSO2 runs low, whereas at low values it runs high. In addition, it should be noted that intravascular oxygenation may not always accurately reflect intracellular oxygen availability. The reasons for the variable relationship between rSO2 and SjO2 between patients (despite the excellent correlation in individual patients) are not entirely clear. The monitor was designed for adult use, and technical adjustments for differing age groups may be required in view of the differing head shapes and thickness of extra-cerebral (superficial) tissues. Some concern has been expressed that, in adults, rSO2 is excessively contaminated by signal from blood in the extra-cerebral tissues. Spatial resolution is likely to be achieved more easily in the paediatric age group, due to decreased thickness of the superficial extra-cerebral tissues [23]. It should also be noted that the vascular composition of the brain is likely to change during CPB and circulatory arrest. As rSO2 depends on the weighted contributions of the differing vascular compartments, alterations in the latter will affect the relationship between rSO2 and SjO2.

However, there are obvious limitations of NIRS monitoring for detection of cerebral ischaemia. A drop in rSO2 is not apparent in cases of cerebral infarction caused by embolism. Hence, rSO2 can remain unchanged when the emboli cause cerebral ischaemia at a site other than the NIRS sampling site and, thus, NIRS is incapable of detecting hypoperfusion in the basilar region. The cerebral oximeter has been cleared for use as a trend monitor; the preferred approach is to rely primarily on a relative measure of oxygen imbalance. The concept of a 20% rSO2 decline as indicative of clinically significant imbalance has been established in a wide range of studies [24].

One of our patients developed a hypoxic encephalopathy. He was presented as an emergent case with type-A dissection continuing in both common carotid arteries. After induction of anaesthesia, resuscitation became necessary and, after emergency thoracotomy, a semi-arch procedure was done with a moderate hypothermic circulatory arrest time of 34 min and bladder temperature of 25 °C. However, in this case, we did not see any significant drop in oxygen saturation below 55% longer than 2 min even during BACP in the course of the surgical procedure period. This led us to the assumption of preoperative cerebral malperfusion and subsequent hypoxic encephalopathy.

Postoperative organic psychosyndrome occurred in three patients (23%), which is comparable to previous reports. One study comparing ACP and RCP noted an overall incidence of temporary neurological dysfunction (TND) of 28.1%, which was similar to our observed incidence [25].

Age of the patients, female gender, acute dissection and aortic valve replacement may be independent predictors of transient neurological deficits. In our analysis of our small cohort, we did not see a significant connection between transient delirium and these independent predictors, which may also be explained by differing definitions of transient neurological deficits along with exclusion of cognitive disorders.

We conclude that aortic arch surgery with MHCA and BACP accompanied by neuromonitoring employing NIRS facilitates online monitoring of cerebral oxygenation and early detection of malperfusion. Especially in the setting of MHCA and unilateral perfusion, it timely indicates deoxygenation of the contralateral hemisphere. According to our findings, selective BACP combined with moderate systemic
hypothermia is our method of choice. Especially in the group of old and co-morbid patients, the method of MHCA combined with BACP accompanied by neuromonitoring allows individualised brain protection including more tepid temperatures with satisfactory results including shorter operating times. However, more experience with NIRS is needed for adjusting the individual needs for sufficient brain perfusion and for tailoring extensive aortic arch surgery to both the needs and the risks of very co-morbid patients in order to yield satisfactory outcomes in this high-risk cohort of patients.

References


Appendix A. Conference discussion

Dr W Harringer (Braunschweig, Germany): I do fully agree with your conclusion.

Our use of near-infrared spectroscopy is a routine adjunct in aortic arch surgery for the last 10 years. In our experience it has been extremely helpful in comparing the perfusion of both brain hemispheres, particularly in patients with acute aortic dissection extending into the head vessels. Now, you’ve demonstrated on your last slide that one of the biggest disadvantages of near-infrared spectroscopy is the lack of information about the status of brain stem perfusion where the most ischaemia-susceptive neurons are located. But it does give you a good impression what is going on with your brain perfusion, especially in patients with no or mild systemic hypothermia.

I would like to address the following questions to you:

First, did you try to correlate your near-infrared spectroscopy measurements with any other methods of neuromonitoring in order to get an impression about the value?

Second, did you see a difference in the duration of regional oxygen saturation drop below 55% in patients with or without transient neurological deficit? In other words, was the time period of drop below 55% longer in the patients that develop a transient neurological deficit?

And the last question is, what was your brain perfusion temperature and did you have to alter brain perfusion with drugs in order to achieve appropriate oxygenation values?

I would like to congratulate you once again on your results and hope to hear of the results in a bigger patient cohort in the future.

Dr Harringer: The first question, no, we didn’t match this with other neuromonitorings. We have tried it with transcranial doppler, but the setting was hard in our OR because of shifting of the system. So we did not have good and exact results.

And the second question, the duration. No, we didn’t see any difference in the duration and drop in cerebral oxygen saturation in patients with or without transient delirium and the drop.

Concerning the third question, we always gave 1 gram prednisolone before surgery and also the head was cooled with an icecap.

Dr Harringer: What was your brain perfusion temperature?

Dr Harrer: And the brain perfusion temperature is 23 degrees Celsius.

Dr Harringer: And no vasodilators into the cerebral perfusion?

Dr Harer: No.

Dr R Bonser (Birmingham, United Kingdom): How soon after changing from unilateral to bilateral did you see an increase in your NIRS signal, how soon afterwards.
**Dr Harrer**: After 2 minutes.

**Dr Bonser**: Within 2 minutes?

**Dr Harrer**: Yes.

**Dr T. Carrel** (Berne, Switzerland): Did you assess the haemoglobin level of the perfusate? Because this is a question that has never actually been answered. Usually we start perfusion with the blood which is in the machine already diluted. What did you have for haematocrit level of the perfusate?

**Dr Harrer**: Our perfusion pressure from the right axillary was between 40 and 60 mm Hg. And our haemoglobin level was between 8 and 10 mg dl⁻¹.