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There is a need for monitoring of cerebral perfusion during cardiac surgery to reduce neurological complications. Cerebral perfusion is a major factor for regional and global imbalance in oxygen supply-demand, which may result in brain injury following cardiac surgery. Cerebral oximetry (near infrared spectroscopy) is a means to monitor regional cerebral perfusion. It was developed as a non-invasive technology, similar to pulse oximetry, for the continuous assessment of cerebral blood flow. Published studies have demonstrated that the use of cerebral oximetry reduces both postoperative cognitive impairment and the length of hospital stay.

## Introduction

Open heart surgery has become increasingly common since first performed by Gibbon in 1953. The average age and the number of co-morbidities in these patients have also increased. Cerebral injury after cardiac surgery is a dreaded outcome and is associated with longer hospital stays, including intensive care unit stays and increased mortality.<sup>1</sup> Morbid neurological outcome after cardiac surgery is classified as type 1 (cerebral death, non-fatal stroke, and new transient ischaemic attack) or type 2 (new intellectual deterioration or new seizure).<sup>2</sup>

The incidence of cerebral complications after cardiac surgery is age-related.<sup>3,4</sup> The incidence of stroke after coronary artery bypass graft surgery (CABG) is less than 1% in patients under 64 years old, 5% in patients aged 65 to 75 years, and 7 to 9% in patients older than 75 years. Neurocognitive decline occurs more frequently than stroke: 60% at 1 week after surgery, and 25 to 30% between 2 months and 1 year.<sup>3</sup>

## Causes of brain injury

Brain injury following cardiac surgery can be focal, global, or diffuse (multifocal). It is usually attributed to two main causes: embolisation (macro/micro) and compromised cerebral blood flow, although systemic inflammatory response has also been implicated.<sup>2,3</sup>

Embolisation is probably a major cause of neurological injury after cardiac surgery. These emboli could be from aortic atheromas, platelet-fibrin and leukocyte aggregates and bubbles from the cardiopulmonary circuit or surgical field.<sup>3</sup>

Hypoperfusion is another major cause of brain injury during cardiac surgery. Cerebral perfusion pressure is usually kept above 50 mm Hg during CABG to avoid neurological injury as intra-operative hypotension has been associated with hypoxic-ischaemic brain injury.<sup>5</sup> Tufo et al<sup>4</sup> reviewed the preoperative and postoperative neurological, psychometric, and behavioural observations in a prospective study of 100 patients undergoing open heart surgery. There was a three-fold increase in the occurrence of cerebral complications when mean arterial pressure (MAP) fell below 40 mm Hg than if MAP was maintained above 60 mm Hg. Systolic blood pressures below 50 mm Hg for 10 minutes or longer increased the risk of postoperative neurological complications four-fold.

Gold et al<sup>6</sup> randomised patients into two groups during cardiopulmonary bypass (CPB). One group (n=124) had high MAP of 80 to 100 mm Hg, achieving a mean perfusion pressure of 70 mm Hg using flow indices of 1.9 to 2.3 L/min/m<sup>2</sup> and vasoactive drugs. The other group (n=124) had low MAP of 50 to 60 mm Hg during CPB. The alpha-stat protocol for blood gas management was used and the temperature was cooled to 28 to 30°C. The impact of the MAP strategy on outcome was assessed (ie mortality, cardiac mortality, neurological morbidity, cognitive decline, and deterioration in quality of life). The patients were observed prospectively for 6 months after the operation and the group with high MAP during CPB had fewer cardiac/central nervous system complications (4.8% vs 13%; P=0.026) and fewer strokes (2.4% vs 7.2%; P=0.076). For each of the outcomes, the trend favoured the higher MAP group.

Caplan and Hennerici<sup>7</sup> postulated that low perfusion pressure and related changes

### Key words

Cardiac surgical procedures; Monitoring, intraoperative; Oximetry; Perfusion; Spectroscopy, near-infrared

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in the dynamics of blood flow in the cerebral arteries during cardiopulmonary surgery affect the clearance and destination of embolic particles. The decreased flow in patients with lower MAP leads to lower cerebral perfusion and this probably impedes clearance of micro-emboli from the brain, resulting in cerebral injury. In addition, the decreased perfusion may limit blood flow to regions rendered ischaemic by embolic events.

There is a need for monitoring of cerebral perfusion during cardiac surgery to reduce neurological complications. Cerebral perfusion is a major factor for regional and global imbalance in oxygen supply-demand which may result in brain injury following cardiac surgery.

### Cerebral monitoring during cardiac surgery—technical considerations

Cerebral oximetry (near infrared spectroscopy [NIRS]) is a means to monitor regional cerebral perfusion. It was developed as a non-invasive technology, similar to pulse oximetry, for continuous assessment of cerebral blood flow (Table).

Near infrared spectroscopy has a light source of two known wavelengths (730 and 810 nm). Optical bundles (optodes) transmit light from the source to the tissue and this is then detected by a light detector (photo diode/photomultiplier). It uses one transmitter and two receptors. The computer program will then process the information with an algorithm to give a reading for cerebral oxygenation.<sup>8,9</sup>

The probe is usually placed on the skin overlying the frontal-temporal region as recommended by the manufacturer (<http://www.somanetics.com>). Optimum contact with the skin is essential to avoid signal contamination. This can be achieved by avoiding areas with hair to ensure maximal skin contact. Absorption of light by the hair follicles even after shaving may lead to a very low return of signals.<sup>10</sup> Just like the pulse oximeter, wrong sensor location or a poorly applied sensor with inadequate skin contact may result in the emitter's light reaching the detector without passing through blood-perfused tissues (optic shunting).<sup>11</sup> This may result in physio-optic dissociation with the light being shunted externally or within the tissue.<sup>11</sup>

The assumption is that light in the near infrared (NIR) range readily penetrates the skin, skull, and deeper cerebral tissues. The transmitted light takes a 'banana-shaped' pathway through the skull to the detectors.<sup>9</sup> Another assumption is that few biological substances absorb NIR, except for haemoglobin (Hb) and cytochrome aa<sup>3</sup>, which show a detectable change in NIR absorption in response to hypoxia. Each chromophore has a unique absorbance spectrum; oxygenated Hb absorbs less red and more infrared

## 心臟外科手術中的腦氧飽和度

在心臟外科手術過程中，需要對腦血流灌注進行監測，以減少神經系統併發症。腦血流灌注是引起全身與局部氧氣供需不平衡的主要因素，可導致心臟外科手術後的腦創傷。腦氧飽和度（近紅外光譜技術）是用於監測局部腦血流灌注的一種方法，與脈搏血氧飽和度相似，屬非侵入性的技術，對腦血流量進行持續評估。已發表的研究報告顯示，應用腦血流灌注監測能減少術後所出現的認知障礙，以及縮短留院時間。

TABLE. Comparison of pulse oximetry and cerebral oximetry\*

	Pulse oximetry	Cerebral oximetry
Pulsatility	Pulsatile	Non-pulsatile
Light transmission	Transmission (usually)	Reflectance
Wavelength	660/940 nm	730/810 nm
Arterial component	Mainly arterial	25% Arterial:75% venous
Oxygen saturation	Hb (arterial)	Cerebral venous saturation
LED	1 Emitter/1 sensor	1 Emitter/2 sensors
Validation	In volunteers	In volunteers
Limitation	Diathermy	Diathermy

\* Hb denotes haemoglobin and LED light emitting diode

than deoxygenated Hb.<sup>8,12</sup>

Cerebral oximetry measures the average oxygen saturation in tissue. Once the probes are established, it is important to correlate changes in the reading with changes in physiological data (changes in blood pressure, end-tidal carbon dioxide and oxygenation). These changes are indications of cerebral perfusion.

Two cerebral oximetry monitors are available—NIRO (Hamamatsu Photonics, Japan) and INVOS (Somanetics Corporation, Troy [MI], US)—of which INVOS has been approved for use by the Food and Drug Administration.<sup>8,9,12</sup> The regional Hb oxygen saturation index (rSO<sub>2</sub>) is displayed in numeric form.

### Near infrared spectroscopy—accuracy

The measurement of rSO<sub>2</sub> is independent of weight, height, head size, and gender.<sup>12</sup> However, the reading may be affected by sensor position and by haem compounds (methemoglobinaemia, carboxyhemoglobinaemia, foetal Hb) and non-haem compounds (bilirubin, biliverdin).<sup>12</sup>

Congenital, traumatic, and surgical skull defects may signal attenuation and inaccurate readings. Signal contamination can also result from extravascular Hb. Stagnant blood may interfere with accurate measurement of cerebral tissue oxygen saturation.<sup>12</sup>

Sometimes rSO<sub>2</sub> asymmetry may occur, even

in apparently normal healthy patients.<sup>12</sup> When differences exist, it is important to identify other likely causes, such as carotid or intracranial arterial stenosis, intracranial space-occupying lesions, extracranial lesions (haemangioma, excessive frontal sinus fluid, skull defects), old infarcts, and interference from infrared emitting devices.<sup>12</sup> This abnormality may also be technical as a single algorithm cannot accommodate the variations in adult cranial anatomy.<sup>12</sup>

### Threshold of regional haemoglobin oxygen saturation index for intervention

A generally accepted normal absolute value for  $rSO_2$  has not been established.<sup>13</sup> Group mean  $rSO_2$  of  $67 \pm 10$  has been observed in conscious healthy volunteers and cardiac patients.<sup>12</sup> A 20% reduction in  $rSO_2$  from the established baseline is an indication of cerebral oxygenation imbalance and the need for intervention to avoid potential harm to patients.<sup>12</sup>

Patients undergoing carotid artery surgery were noted to have symptoms of regional ischaemia occurring with 20% decline in  $rSO_2$ . Samra et al<sup>14</sup> retrospectively reviewed 99 cases of carotid endarterectomy performed under regional anaesthesia with cerebral oximetry monitoring. Patients were assigned to one of two groups: those with change in mental status or contralateral motor deficits after internal carotid clamping, and those who were asymptomatic. The mean decrease in  $rSO_2$  after carotid occlusion in the group with neurological symptoms was significantly greater than the asymptomatic group. They demonstrated that using 20% decrease in  $rSO_2$  reading from pre-clamp baseline as a predictor of neurological compromise resulted in a sensitivity of 80% and specificity of 82%.

### Reduction of cerebral tissue oxygen saturation—clinical significance

Most advocates for cerebral oximetry monitoring rely on two types of outcomes, mainly a decrease in the incidence of cognitive dysfunction/stroke and a decrease in the length of intensive care unit and hospital stay. The following studies on patients undergoing cardiac and non-cardiac surgery have demonstrated that intra-operative reductions in  $rSO_2$  are associated with postoperative cognitive decline.

In a prospective, observational study by Casati et al,<sup>15</sup> intra-operative cerebral oximetry monitoring was performed in 60 elderly patients during non-vascular abdominal surgery. Cognitive function was assessed using the Mini-Mental State Examination (MMSE) on the day before surgery and 1 week after surgery. The findings demonstrated that reductions in cerebral oximetry readings occurred in 25% of

patients (reductions were defined as  $rSO_2$  decreased to less than 75% of baseline or to less than 80% in cases with baseline  $rSO_2$  of less than 50%). In their study, intra-operative cerebral tissue desaturation did not affect the recovery profile from anaesthesia or the time of discharge from the post-anaesthetic care unit. However, patients with reduced cerebral tissue oxygen saturation readings were found to have a higher incidence of early postoperative decline of cognitive function and longer hospital stays.

Yao et al<sup>16</sup> evaluated the relationship between cerebral oxygen saturation and neuropsychological dysfunction after cardiac surgery. In their study, 90% of patients had episodes of  $rSO_2$  of less than 50% during CPB. Mini-Mental State Examination and antisaccadic eye movement (ASEM) tests were used to assess cognitive function before surgery and 4 to 6 days postoperatively. They found that patients with intra-operative cerebral oxygen desaturation (nadir  $rSO_2 < 35\%$ ) at any time during surgery had a significantly higher incidence of postoperative ASEM/MMSE impairment.

The limitation for using MMSE and ASEM is that both are not part of a standard neuropsychological test battery for evaluation of mental function.<sup>10</sup> They are not sensitive tests for cognitive function.<sup>10</sup> However, they can be done at the bedside and have been used for assessment of cognitive function. The results in the two studies above suggested a decline in cognitive function in patients who had intra-operative cerebral tissue desaturation.

In a retrospective study by Goldman et al,<sup>17</sup> patients ( $n=1034$ ) who had cerebral oximetry monitoring during cardiac surgery were compared with patients ( $n=1245$ ) who had cardiac surgery without cerebral oximetry monitoring. In the group with cerebral oximetry monitoring, cerebral oxygen delivery was optimised during surgery by modifying oxygen delivery, oxygen consumption, and oxygen carrying capacity to maintain the  $rSO_2$  value at or near patient's pre-induction baseline. The interventions included an increase in inspired oxygen ( $FiO_2$ ), adjusting head or cannula position, an increase in arterial carbon dioxide ( $PaCO_2$ ), increasing MAP, increasing pump flow/cardiac output, increasing anaesthetic depth, administering nitroglycerin to dilate cerebral vessels, and administering packed red cells to increase haematocrit to greater than 23%. They demonstrated a lower incidence of permanent stroke (0.97% vs 2.5%,  $P<0.044$ ), less need for prolonged ventilation (6.8% vs 10.6%,  $P<0.0014$ ), and risk-matched reduction in hospital stay (0.2 days vs 2.3 days depending on the New York Heart Association class,  $P<0.046$ ) in the group who had intra-operative cerebral oximetry monitoring with optimisation of cerebral oxygen delivery.

Murkin et al<sup>18</sup> did a randomised prospective

study of patients (n=200) in which one group (n=100) had intra-operative cerebral oximetry monitoring with specific intervention to maintain cerebral oxygen delivery, while the other group (control; n=100) underwent blinded rSO<sub>2</sub> monitoring but without any interventions. Interventions included raising the pump flow, increasing the MAP, normalising the PaCO<sub>2</sub>, deepening the anaesthesia, increasing FiO<sub>2</sub> and using pulsatile perfusion whenever cerebral desaturation occurred to allow the rSO<sub>2</sub> to increase to greater than 75% of baseline values. Although there was no significant difference in the overall incidence of adverse complications, patients in the control group (P=0.014) had longer periods of cerebral desaturation and longer intensive care unit stays (P=0.029). The major organ morbidity and mortality (MOMM) between the two groups was compared. The Society of Thoracic Surgeons designed MOMM to look at the incidence of stroke, renal failure requiring dialysis, prolonged ventilation of more than 48 hours, deep sternal infection, re-operation, and death.<sup>19</sup> The control group had significantly more MOMM (P=0.017) than those who had cerebral oximetry monitoring with interventions to improve cerebral oxygenation.

### Cerebral oximetry in cardiac surgery

In addition to a reduction in the incidence of neurological injury and duration of hospital stay,<sup>10,15,17</sup> intra-operative use of cerebral oximetry monitoring has been associated with early detection of potentially catastrophic brain injury requiring immediate intervention.

Janelle et al<sup>20</sup> reported a case of DeBakey type 1 aortic dissection undergoing surgery with cerebral oximetry monitoring. After about 40 minutes of CPB, while the aortic valve was being replaced, profound right hemispheric desaturation occurred despite temperature being maintained at 18°C and presence of an isoelectric electroencephalogram (EEG). The surgeon was informed and the aortic valve replacement was temporarily stopped. The patient was put into hypothermic circulatory arrest. Surgical exploration revealed an extension of the false lumen from the ascending aorta through the right brachiocephalic artery and into right common carotid artery. The arch was repaired under retrograde cerebral perfusion during which there was no improvement in ipsilateral rSO<sub>2</sub> values, and the contralateral rSO<sub>2</sub> continued to decrease. There was prompt improvement of bilateral rSO<sub>2</sub> after reinstatement of CPB via cannulation of the ascending aortic graft. The patient was discharged from the hospital without neurological symptoms on the 11th day after surgery.

In another case, Gottlieb et al<sup>21</sup> reported a 16-month-old patient scheduled for complete repair of acyanotic tetralogy of Fallot. There was a persistently

low rSO<sub>2</sub> (with R<L) after initiation of CPB with MAP higher than expected based on measurements from the left radial artery. Surgical exploration revealed malposition of the aortic cannula with flow being diverted preferentially to the left carotid and subclavian arteries. Re-positioning restored the rSO<sub>2</sub> to baseline values, accompanied by a decrease in MAP as measured on the left radial artery, with no change in the CPB flow rate or anaesthesia depth. This clinical picture of sudden decrease in rSO<sub>2</sub> with increase in MAP reading on the left radial artery recurred twice while the patient was on CPB, requiring reorientation of the aortic cannula. The patient was discharged home on day 8, neurologically intact.

Taillefer and Denault<sup>22</sup> did a systematic review of publications up to February 2004 on cerebral NIRS in adult heart surgery looking at its clinical efficacy. There were methodological limitations in some of the articles reviewed. Most of the papers reviewed were prospective, with rSO<sub>2</sub> collected during surgery and in the postoperative period. There was only one randomised control trial (level II evidence), while the rest were level III to V evidence. In addition, different models were used to measure rSO<sub>2</sub> in the papers reviewed (INVOS and NIRO) and this affects the conclusions of the meta-analysis.

Nevertheless the authors concluded that the articles reviewed had positive results despite the low level of evidence.<sup>22</sup> Specifically, cerebral oximetry was able to give data on local oxygenation, allowing early intervention before long-term neurological deficits occurred. In addition, it had its advantage in cerebral oxygen saturation monitoring during extracorporeal circulation even though there is no pulsatile signal. The use of NIRS as a trend monitor (percent deviation from normal) is beneficial as a decline in rSO<sub>2</sub> is an indication of brain desaturation. There was also a potential cost-saving in early discharge from the intensive care unit.

In a paper by Daubeney et al,<sup>23</sup> vulnerable periods with reduction in rSO<sub>2</sub> during cardiac surgery were identified by observing the regional cerebral oxygenation in children using NIRS. There were reductions in rSO<sub>2</sub> before bypass (during handling and dissection around the heart prior to and during caval cannulation). The rSO<sub>2</sub> was again noted to be reduced during re-warming in the early post-bypass period and before discontinuation of CPB. This is consistent with the findings of Nakajima et al<sup>24</sup> who studied patients undergoing cardiac surgery with continuous jugular bulb oxygen saturation monitoring. They observed a 3% decrease in jugular bulb oxygen saturation per degree increase in body temperature during the re-warming phase. Regional cerebral oxygenation correlated positively with jugular bulb venous saturation ( $r=0.69$ ,  $P<0.0001$ ) by Daubeney et al.<sup>25</sup>

## Multimodality monitoring in cardiac surgery

A major disadvantage of cerebral oximetry is that it examines a very superficial focal area of the brain. Other vulnerable areas may be outside the path of light, eg the parietal lobes or deeper structures.<sup>26</sup> In addition, the underlying assumption of a constant ratio of 25% arterial:75% venous blood volume in the brain tissue may change during CPB and with variations in respiration and patient positioning.<sup>26</sup> With combined use of transcranial Doppler (TCD) to measure blood flow in the middle cerebral and anterior cerebral arteries, and NIRS to measure the rSO<sub>2</sub> of blood in the frontal lobe, it is possible to monitor up to 70% of the blood flow distribution to a cerebral hemisphere.<sup>27</sup>

The use of more than one cerebral monitoring (multimodality monitoring) during cardiac surgery was advocated by Lozano and Mossad.<sup>13</sup> They described a multimodality neurophysiologic monitoring algorithm to identify and manage the vulnerable periods during the various stages of CPB and deep hypothermic circulatory arrest.

Using a similar algorithm strategy, Yeh et al<sup>28</sup> described the rapid recognition and treatment of cerebral air embolism in a child undergoing Fontan procedure. The child had monitoring which included transoesophageal echocardiography, arterial pressure, central venous pressure, electrocardiography, pulse oximetry, 8-channel EEG, right middle cerebral artery TCD ultrasonography, and bilateral cerebral oximetry. Intra-operative cerebral air embolism was detected by TCD, accompanied by a sharp decline in rSO<sub>2</sub>. A neuroprotective strategy was adopted and EEG near-

silence was achieved with rapid cooling. Retrograde cerebral perfusion was initiated. Antegrade cerebral perfusion was established after successful management of the air embolism, with return of EEG and rSO<sub>2</sub>. In this case, there were no adverse neurological outcomes.

## Management of cerebral desaturation during cardiopulmonary bypass

There are periods during CPB when the rSO<sub>2</sub> has been noted to decrease.<sup>21,23</sup> At the initiation of CPB, a decrease in rSO<sub>2</sub> could be secondary to haemodilution. There may also be reduction in rSO<sub>2</sub> during the re-warming after CPB due to an imbalance in oxygen supply and demand. Other reasons for a decrease in rSO<sub>2</sub> could be from an inadequate bypass flow, hypocarbia, inadequate MAP, or anaemia.

Therapeutic approaches for a reduced cerebral tissue saturation will be slower re-warming, increasing cerebral blood flow (increasing arterial PaCO<sub>2</sub> tension), decreasing the cerebral metabolic rate for oxygen (anaesthesia), increasing the oxygen content (red cell transfusion), and increasing the flow rate.<sup>29</sup>

## Conclusions

Cerebral oximetry allows continuous non-invasive monitoring of brain oxygen saturation. It may help identify vulnerable periods during cardiac surgery, which may require immediate interventions to avoid adverse events. Published outcome studies of cerebral oximetry monitoring with active interventions have demonstrated reduced postoperative cognitive decline and length of hospital stay.

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