Near-infrared Spectroscopy to Indicate Selective Shunt Use During Carotid Endarterectomy

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WHAT THIS PAPER ADDS

Several monitoring modalities are available to guide selective shunt use during carotid endarterectomy performed with the patient under general anesthesia. In this prospective study, to our knowledge the largest series to date evaluating near-infrared spectroscopy (NIRS) and transcranial Doppler (TCD) compared with electroencephalography, we found moderate positive predictive values but high negative predictive values for both techniques. Therefore, we propose that for clinicians who routinely shunt, both NIRS and TCD could independently be helpful to reduce unnecessary shunt use. However, taking methodologic flaws into account, such as the availability of a sufficient temporal window and the need for skilled personnel in TCD registry, NIRS may become the preferred monitoring technique in the near future.

Objectives: This study assessed the value of cerebral near-infrared spectroscopy (NIRS) and transcranial Doppler (TCD) in relation to electroencephalography (EEG) changes for the detection of cerebral hypoperfusion necessitating shunt placement during carotid endarterectomy (CEA).

Methods: This was a prospective cohort study. Patients with a sufficient TCD window undergoing CEA from February 2009 to June 2011 were included. All patients were continuously monitored with NIRS and EEG. An intraluminal shunt was placed, selectively determined by predefined EEG changes in alpha, beta, theta, or delta activity. Relative changes in regional cerebral oxygen saturation (rSO2) in the frontal lobe and mean blood flow velocity (Vmean) 30 seconds before carotid cross-clamping versus 2 minutes after carotid cross-clamping were related to shunt placement. Receiver operating characteristic curve analysis was performed to determine the optimal thresholds. Diagnostic values were reported as positive and negative predictive value (PPV and NPV).

Results: Of a cohort of 151 patients, 17 (11%) showed EEG changes requiring shunt placement. The rSO2 and Vmean decreased more in the shunt group than in the non-shunt group (mean ± standard error of the mean) 21 ± 4% versus 7 ± 5% and 76 ± 6% versus 12 ± 3%, respectively (p < .005). Receiver operating characteristic curve analysis revealed a threshold of 16% decrease in rSO2 (PPV 76% and NPV 99%) and 48% decrease in Vmean (PPV 53% and NPV 99%) as the optimal cut-off value to detect cerebral ischemia during CEA under general anesthesia.

Conclusions: Compared with EEG, we found moderate PPV but high NPV for NIRS and TCD to detect cerebral ischemia during CEA under general anesthesia, meaning that both techniques independently may be suitable to exclude patients for unnecessary shunt use and to direct the use of selective shunting. However, the optimal thresholds for NIRS remain to be determined.

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Article history: Received 19 December 2012, Accepted 2 July 2013, Available online 21 August 2013
Keywords: Carotid endarterectomy, Near-infrared spectroscopy, Selective shunt placement, Complications of carotid endarterectomy

INTRODUCTION

Carotid endarterectomy (CEA) is the treatment of choice to prevent future cerebrovascular events in symptomatic patients with a high-grade stenosis of the internal carotid artery.1 However, the procedure itself carries a risk of stroke. Strokes with an onset during CEA are mainly caused by thrombosis, embolism, or intraoperative ischemia related to hypoperfusion during cross-clamping (CC) of the carotid artery.2 Cerebral ischemia during CC may be prevented by placement of an intraluminal shunt, which may reduce the duration that blood flow to the brain is interrupted. However, routine shunting may result in
unnecessary shunt use in approximately 85% of patients because most patients have sufficient collateral cerebral perfusion during CC. Further potential disadvantages of shunting include carotid artery dissection, shunt plaque embolization, and inadequate shunt flow or shunt thrombosis. A shunt may also limit the exposure of the distal portion of the plaque. Many surgeons therefore prefer selective shunting, but this necessitates the use of a monitoring method to detect cerebral ischemia during a test CC. Use of locoregional anesthesia allows monitoring of cerebral ischemia during selective shunting, but this necessitates the use of a monitoring method to detect cerebral ischemia during a test CC.

Use of locoregional anesthesia allows monitoring of cerebral ischemia during an awake patient and can be regarded as the accepted standard for detection of cerebral ischemia during CC. In contrast, objective detection of cerebral ischemia in patients under general anesthesia is more challenging. In experienced hands, interpretation of changes in electroencephalography (EEG) is the most widely used applied technique to detect cerebral ischemia and to decide whether a shunt is needed, with high positive predictive value (PPV) and high negative predictive value (NPV). However, implementation of EEG is associated with high procedural costs, and proper interpretation requires personnel experienced in clinical neurophysiology. Moreover, pre-existing EEG abnormalities in patients presenting with severe stroke or anesthetic-induced changes make interpretation of the EEG more difficult, or even impossible. Transcranial Doppler (TCD) ultrasound monitoring of the mean blood flow velocity (Vmean) in large cerebral arteries, such as the middle cerebral artery (MCA), is widely used to obtain additional information regarding cerebral hemodynamics. Although TCD measurements are related to EEG changes, they are not a parameter of cerebral oxygenation. Moreover TCD monitoring fails in up to 15% of patients because of an insufficient temporal bone window.

A third non-invasive technique to detect cerebral ischemia is by monitoring changes in regional cerebral oxygen saturation (rSO2) in the frontal lobe by near-infrared spectroscopy (NIRS). NIRS is easy to apply in all patients and is relatively low in cost because it offers information about cerebral oxygenation without the need for specialized personnel. NIRS has been widely applied in cardiac surgery, providing some evidence that NIRS-guided brain protection protocols might lead to reduced neurologic complications and improved patient outcomes. In the present study, we assessed the value of NIRS and TCD in relation to EEG changes for the detection of cerebral hypoperfusion necessitating shunt placement during CEA.

METHODS

Patients

This prospective cohort study included patients with a carotid stenosis >70%, as discussed by a multidisciplinary team. The severity of the carotid artery stenosis was assessed by carotid color Doppler-assisted duplex ultrasound imaging and confirmed by magnetic resonance angiography or computed tomography angiography. Stenosis was categorized on a four-point scale as <50%, 50–70%, 70–99% stenosis, or occlusion.

CEA protocol

All patients underwent CEA under general anesthesia. Induction of anesthesia was achieved with sufentanil (0.3–0.7 μg/kg), propofol (0.5–2.0 mg/kg), and rocuronium (0.3–0.5 mg/kg), and was maintained with sevoflurane, aiming at a minimum alveolar concentration value between 0.5% and 1%. Mean arterial pressure (MAP) was measured invasively using a 20-gauge catheter (1.1 mm internal diameter) placed in the radial artery. Until the carotid artery was declamped, MAP was kept below preoperative baseline values and 20% above. If required, vasoactive medication was administered to increase MAP. CEA was performed in a standardized way by an experienced vascular surgeon or by a vascular trainee under supervision. Heparin (5000 U) was administered intravenously 3 minutes before CC of the carotid artery. An intraluminal Javid shunt was placed selectively and based solely on predefined EEG changes during at least 2 minutes of a test CC. Sevoflurane administration was discontinued at the end of the procedure. The patient was extubated after the return of spontaneous respiration and was transferred to the recovery ward.

Monitoring techniques

Patients were continuously monitored using EEG, TCD, and NIRS during the entire procedure. Blood pressure, TCD, and NIRS data were stored on a hard disk for off-line analysis by an investigator blinded for shunt use and clinical outcome.

EEG protocol

Scalp electrodes were positioned before CEA according to the International System. A 16-channel montage (FP1/2, F7/8, T3/4, T5/6, O2/2, F3/4, C3/4, and P3/4) with Cz as the common reference was used. A preoperative EEG was obtained for all patients on the nursing ward or in the operating room. EEG signals were continuously monitored during surgery using a Micromed system device (Micromed Inc., Treviso, Italy) with a sample rate of 512 Hz. During the 2 minutes of test CC, changes in the EEG were assessed under supervision of a clinical neurophysiologist. The occurrence of new delta or theta activity was considered indicative for the development of cerebral ischemia in a predefined way.

TCD assessment

For measurement of the Vmean in the MCA, a DWL Multidop X4 pulsed Doppler transducer (DWL Elektronische Systeme GmbH, Singen, Germany), gated at a focal depth of 45–
60 mm, was placed over the temporal bone to insonate the main stem of the ipsilateral MCA. In the contralateral hemisphere, the V in the anterior cerebral artery was monitored. Once the optimal signal-to-noise ratio was obtained, the TCD transducer was fixed in place with a head frame, and \( V_{\text{mean}} \) was recorded continuously.

NIRS assessment

Two sensors were placed on the forehead, and continuous, bilateral \( rSO_2 \) measurements were performed using an Invos Cerebral Oximeter (Invos 5100C, Somanetics Corp, Troy, MI). NIRS allows continuous monitoring of regional cerebral oxygen saturation by penetrating the scalp and brain tissue, whereby the skin, skull, and other tissues are relatively transparent to near-infrared wavelengths of light. Changes in concentrations of oxygenated and deoxygenated hemoglobin are measured by a modified Beer–Lambert method. Oxygenated and deoxygenated hemoglobin have different wavelengths, which can be used to define the ratio of oxygenated hemoglobin to total tissue hemoglobin. By using two detectors, the light reflected and transmitted by the superficial extracranial tissues is subtracted.

Study parameters and data analysis

The percentage change in \( rSO_2 \) (\( \Delta rSO_2 \)), \( V_{\text{mean}} \) (\( \Delta V_{\text{mean}} \)), and MAP (\( \Delta MAP \)) elicited by CC was calculated by subtracting the averaged values of \( rSO_2 \), \( V \), and MAP for 30 seconds before the CC (pre-CC) test from the averaged values for \( rSO_2 \) 30 seconds assessed 2 minutes after CC (post-CC). This was divided by the pre-CC value. Subsequently, \( \Delta rSO_2 \), \( \Delta V_{\text{mean}} \), and \( \Delta MAP \) were related to shunt placement, our primary end point, and to clinical outcome of stroke or death, our secondary end point.

Statistical analysis

For dichotomized factors, we used cross tabs and chi-square tests \((n > 5)\) or Fisher exact tests \((n < 5)\) to calculate \( p \) values. Continuous characteristics, presented as mean ± standard deviation, were analyzed using a paired or unpaired Student \( t \) tests when appropriate. Subsequently \( \Delta rSO_2 \), \( \Delta V_{\text{mean}} \), and \( \Delta MAP \) were calculated and are presented as mean ± standard error of the mean. To determine the optimal \( \Delta rSO_2 \) and \( \Delta V_{\text{mean}} \) cutoff value for cerebral hypotension requiring shunt placement, receiver operating characteristic (ROC) curves were analyzed. The diagnostic performance is expressed as the PPV and NPV with the 95% confidence interval (CI). All analyses were performed using SPSS 20.0 software (SPSS Inc, Chicago, IL, USA). Values of \( p < .05 \) were considered significant.

RESULTS

Patient characteristics

Within the study timeframe, 294 patients underwent CEA, of which 274 (93%) had a sufficient TCD window. Because of logistic reasons, the study included 151 patients, who were a mean age of 70 ± 9 years. Most patients underwent CEA because of a high degree of symptomatic stenosis (Table 1). The median time between the last neurologic symptoms and subsequent CEA in our tertiary referral center was 27 days (interquartile range, 18–51 days). The excluded patients did not significantly differ from the study population regarding shunt usage. Relevant EEG changes occurred in 17 patients (11%), and an intraluminal shunt was inserted. As reported in Table 1, baseline characteristics of patients who did and who did not receive an intraluminal shunt did not differ significantly, with the exception of occlusion of the contralateral internal carotid artery, which was more frequently present in the shunt group (10% vs. 29%; \( p = .03 \)). The 30-day death/stroke rate was 3.3% \((n = 5)\). One patient (0.7%) died 13 days after surgery because of vegetative endocarditis without cerebrovascular complications. Four patients (2.6%) sustained a stroke with an intraoperative onset, of which three were defined as minor strokes and one as a major stroke (without useful recovery of function). No postoperative stroke occurred. More strokes occurred in the shunted group \((2 [11.7%])\) than in the non-shunted group \((2 [1.5%]; Table 2)\). Three of four intraoperative strokes were identified with EEG.

Measurements

The changes in \( rSO_2 \), \( V_{\text{mean}} \), and MAP elicited by CC are presented in Fig. 1. In the 134 patients who did not receive a shunt, the \( \Delta rSO_2 \) and \( \Delta V_{\text{mean}} \) of \(-7 \pm 0\%\) and \(-12 \pm 3\%\) were smaller than the respective values of \(-20 \pm 1\%\) and \(76 \pm 6\%\) in the 17 patients who did receive a shunt (both \( p < .05 \)).

ROC curve analysis

Analysis of the ROC (Fig. 2) curve showed an area under the curve of 0.98 (95% CI 0.96–1.00) for \( \Delta rSO_2 \) to indicate shunt requirement as determined from EEG changes by the current protocol. An optimal \( \Delta rSO_2 \) cutoff value of a 16% decrease of pre-CC \( rSO_2 \) was also calculated. With this cutoff value, a PPV of 76% (95% CI 54–89%) and an NPV of 99% (95% CI 96–100%) were obtained. To indicate shunt placement by TCD, a cutoff value of a 48% decrease in \( V_{\text{mean}} \) was found, with an area under the curve of 0.94 (95% CI 0.86–1.00), a PPV of 53% (95% CI 36–70%), and an NPV of 99% (95% CI 96–100%; Table 3). In 21 patients, the threshold of \( \Delta rSO_2 \) of \(-16\%\) or less resulted in five patients with false-positive results, and with a threshold of \( \Delta V_{\text{mean}} \) \(-48\%\) or lower, nine more patients would have been wrongly identified. No new neurologic deficits were found when these false-positive patients recovered from anesthesia.

In addition to EEG changes, the two patients in the shunt group who sustained a stroke also showed decreases below \( \Delta rSO_2 \) and \( \Delta V_{\text{mean}} \) thresholds.

DISCUSSION

In this study, we determined the diagnostic value of intraoperative NIRS and TCD monitoring to diagnose cerebral hypoperfusion detected by EEG during test clamping of the
carotid artery in patients undergoing CEA under general anesthesia. We found moderate PPV but high NPV values for NIRS and TCD.

The existing literature does not elucidate whether selective or routine shunting has a more beneficial clinical outcome, and the consensus is that the individual surgeon should select the method with which he or she is most comfortable.7,14,15 If shunting will be performed selectively, we propose that NIRS and TCD could independently exclude cerebral ischemia in patients undergoing CEA under general anesthesia and that both monitoring techniques could therefore be helpful in reducing unnecessary shunt use. In fact, if the thresholds we found in our study of a 16% decrease in rSO2 and a 48% decrease in $V_{mean}$ had been used instead of routine shunting, the number of patients who were shunted unnecessarily could have been reduced by 85% (from 134 to 21) and 78% (from 134 to 30), respectively.

NIRS may become the preferred monitoring technique in the near future because TCD requires specialized personnel and fails in up to 15% of patients as a result of an insufficient temporal bone window. Both techniques may be suitable to direct the use of selective shunting during CEA. The number of false-positive results for both techniques is high; however, further data collection and analysis are required to define the optimal and most accurate NIRS threshold. Until this threshold is defined, we suggest the use of EEG monitoring for selective shunt use.

Several studies have discussed the value of TCD in the detection of hypoperfusion based on EEG changes in patients undergoing CEA under general anesthesia. Two studies, however, based the decision for shunt use purely on previously defined TCD thresholds.16,17 In another study, a cutoff value of a 65% decrease in $V_{mean}$ was determined, and a sensitivity of 80% and a specificity of 95% was found.18 Furthermore, a reduction in blood flow velocity of 70% was associated with a PPV of 56% and an NPV of 99%.5

We previously conducted a systematic review that compared the value of NIRS during CEA in relation to existing cerebral monitoring techniques.19 Several studies aimed to determine whether NIRS could be used to determine the need for shunt placement.20–25 However, we

Table 1. Characteristics of all patients at baseline and according to shunt use.

<table>
<thead>
<tr>
<th>Variable</th>
<th>All patients, n = 151</th>
<th>Shunt group, n = 17</th>
<th>Non-shunt group, n = 134</th>
<th>p-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender (M)</td>
<td>117 (78%)</td>
<td>15 (88%)</td>
<td>102 (76%)</td>
<td>0.26</td>
</tr>
<tr>
<td>Side (right)</td>
<td>63 (42%)</td>
<td>6 (35%)</td>
<td>57 (43%)</td>
<td>0.57</td>
</tr>
<tr>
<td>Age (years; mean ± SD)</td>
<td>70 ± 9</td>
<td>69 ± 8</td>
<td>70 ± 10</td>
<td>0.72</td>
</tr>
<tr>
<td>Atrial fibrillation</td>
<td>14 (9%)</td>
<td>1 (6%)</td>
<td>13 (10%)</td>
<td>0.61</td>
</tr>
<tr>
<td>Angina pectoris or myocardial infarction</td>
<td>49 (33%)</td>
<td>5 (29%)</td>
<td>44 (33%)</td>
<td>0.78</td>
</tr>
<tr>
<td>Diabetes Mellitus</td>
<td>36 (24%)</td>
<td>4 (24%)</td>
<td>32 (24%)</td>
<td>0.97</td>
</tr>
<tr>
<td>Hypercholesterolemia</td>
<td>134 (89%)</td>
<td>16 (94%)</td>
<td>118 (88%)</td>
<td>0.46</td>
</tr>
<tr>
<td>Peripheral artery disease</td>
<td>34 (23%)</td>
<td>6 (35%)</td>
<td>28 (21%)</td>
<td>0.18</td>
</tr>
<tr>
<td>Hypertension</td>
<td>127 (84%)</td>
<td>16 (94%)</td>
<td>111 (83%)</td>
<td>0.23</td>
</tr>
<tr>
<td>History of CEA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ipsilateral</td>
<td>1 (1%)</td>
<td>0</td>
<td>1 (1%)</td>
<td>0.72</td>
</tr>
<tr>
<td>Contralateral</td>
<td>17 (11%)</td>
<td>2 (12%)</td>
<td>15 (11%)</td>
<td>0.94</td>
</tr>
<tr>
<td>Indication (symptomatic)</td>
<td>133 (88%)</td>
<td>14 (82%)</td>
<td>119 (89%)</td>
<td>0.44</td>
</tr>
<tr>
<td>Degree of ipsilateral stenosis</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50–70%</td>
<td>9 (6%)</td>
<td>2 (12%)</td>
<td>7 (5%)</td>
<td>0.28</td>
</tr>
<tr>
<td>&gt;70%</td>
<td>142 (94%)</td>
<td>15 (88%)</td>
<td>127 (95%)</td>
<td>0.22</td>
</tr>
<tr>
<td>Degree of contralateral stenosis</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;50%</td>
<td>72 (48%)</td>
<td>7 (41%)</td>
<td>65 (49%)</td>
<td>0.57</td>
</tr>
<tr>
<td>50–70%</td>
<td>25 (17%)</td>
<td>3 (18%)</td>
<td>22 (16%)</td>
<td>0.90</td>
</tr>
<tr>
<td>70–99%</td>
<td>24 (16%)</td>
<td>2 (12%)</td>
<td>22 (16%)</td>
<td>0.62</td>
</tr>
<tr>
<td>Occlusion</td>
<td>19 (13%)</td>
<td>5 (29%)</td>
<td>14 (10%)</td>
<td>0.03</td>
</tr>
<tr>
<td>Unknown</td>
<td>11 (7%)</td>
<td>0</td>
<td>11 (8%)</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Table 2. Clinical 30-day outcome.

<table>
<thead>
<tr>
<th>Variable</th>
<th>All patients, n = 151</th>
<th>Shunt group, n = 17</th>
<th>Non-shunt group, n = 134</th>
<th>p-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stroke &lt;30 days</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Major stroke</td>
<td>1 (0.6%)</td>
<td>1 (5.9%)</td>
<td>0</td>
<td>0.11</td>
</tr>
<tr>
<td>Minor stroke</td>
<td>3 (2.0%)</td>
<td>1 (5.9%)</td>
<td>2 (1.5%)</td>
<td>0.30</td>
</tr>
</tbody>
</table>

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concluded that a reliable comparison between these studies is limited because of the lack in standardization of the applied devices, study protocol, and variation in indications for shunt use across studies.

Thus far, only two studies described the relationship between NIRS and EEG changes requiring shunt placement in patients undergoing CEA under general anesthesia with selective shunt use and determined cutoff values. Hirofumi et al. found a decrease of 30% in cerebral oxygenation, with a PPV and NPV of 100%; however, this cutoff value was only based on one patient in whom selective shunt placement was performed. De Letter et al. included 101 patients, of whom 17 (17%) required selective shunt insertion based on EEG. In their search for a cutoff value with an NPV of 100%, which we also consider most important because cerebral hypoperfusion without intraluminal shunt placement may result in irreversible cerebral infarction, we found a cutoff value of 13% rSO₂ decrease. However, as the time point of measuring was not further defined in the study by De Letter et al., and the sample rate was 0.017 Hz instead of a sample rate of 0.14 Hz in the current study, the different cut-off values may not be comparable. Because the case numbers in most studies are small, pooling individual patient data to perform meta-analysis may be a step forward to a higher level of evidence. The use of individual patient data meta-analysis will allow evaluating the

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**Table 1.**

<table>
<thead>
<tr>
<th>Condition</th>
<th>Pre-clamping</th>
<th>Clamping (2 min)</th>
<th>Clamping (10 min)</th>
<th>Post-clamping</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Non-shunted</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(n=134)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAP (mmHg)</td>
<td>95 ± 15</td>
<td>101 ± 15</td>
<td>100 ± 15</td>
<td>88 ± 8</td>
</tr>
<tr>
<td>V&lt;sub&gt;mean&lt;/sub&gt; (cm·s&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>51 ± 16</td>
<td>45 ± 21</td>
<td>44 ± 19</td>
<td>57 ± 22</td>
</tr>
<tr>
<td>rSO₂ (%)</td>
<td>70 ± 8</td>
<td>66 ± 8</td>
<td>66 ± 8</td>
<td>70 ± 9</td>
</tr>
<tr>
<td><strong>Shunted</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(n=17)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAP (mmHg)</td>
<td>96 ± 15</td>
<td>99 ± 11</td>
<td>101 ± 16</td>
<td>86 ± 14</td>
</tr>
<tr>
<td>V&lt;sub&gt;mean&lt;/sub&gt; (cm·s&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>58 ± 24</td>
<td>13 ± 10</td>
<td>61 ± 25</td>
<td>70 ± 28</td>
</tr>
<tr>
<td>rSO₂ (%)</td>
<td>70 ± 10</td>
<td>56 ± 8</td>
<td>67 ± 13</td>
<td>69 ± 12</td>
</tr>
</tbody>
</table>

**Figure 1.** Timeframe. Mean values (± standard deviation) of mean arterial pressure (MAP), mean middle cerebral artery blood velocity (V<sub>mean</sub>), and regional cerebral oxygen saturation (rSO₂) in the frontal lobe were recorded and calculated at the following time points. The grey area indicates clamping period.

**Figure 2.** Receiver operating characteristic (ROC) curves show the accuracy of intraoperative regional cerebral oxygen saturation (rSO₂; dark line) compared with mean middle cerebral artery blood velocity (V<sub>mean</sub>; light line) in detecting cerebral ischemia requiring shunt use detected by electroencephalogram (EEG).
accuracy of NIRS in relation to other patient characteristics, which could ultimately increase the accuracy of NIRS. For example, an occlusion of the contralateral carotid artery may be associated with the need for selective shunt placement.\(^{48,29}\)

The number of patients in our study may seem limited; yet, compared with other studies, we included a relatively high number of patients receiving an intraluminal shunt. Furthermore, the number of strokes in the shunted group was relatively high. This cannot be explained by shunt malfunctioning, because TCD monitoring was also used in all patients, providing direct information to the surgeon on actual shunt function, and no shunt malfunctioning was noticed. In addition, the high stroke rate might be explained by the high-risk patients who undergo operations in our tertiary referral center.

The use of EEG as a reference standard may have influenced our results because the performance of NIRS was studied relative to EEG. Because the neurologic examination in the awake patient allows an absolute determination of cerebral ischemia, it will be interesting to define a \( rSO_2 \) threshold in patients who develop neurologic deficits during CC under local anesthesia. However, whether these data would be transferable to patients undergoing CEA under general anesthesia is disputable as McCleary et al.\(^{30}\) suggest that local anesthesia preserves cerebral autoregulation whereas general anesthesia does not.

Another consideration of our study concerns the technique used for the \( rSO_2 \) measurements. By using two sensors placed on the forehead, the frontal lobe oxygenation was measured in the cerebral tissue mainly perfused by the anterior cerebral artery, whereas the territory of the MCA is more laterally localized. Nevertheless, a comparison of frontally versus temporally placed sensors found that NIRS measurements using a frontal probe are at least as representative as a lateral probe for monitoring cerebral ischemia during CC.\(^{31}\) Several factors can influence the absolute \( rSO_2 \) values, including arterial oxygen saturation, systemic blood pressure, arterial carbon dioxide tension, the hematocrit level, the cerebral blood volume, and if interindividual and intraindividual baseline variability in \( rSO_2 \) is high.\(^{12}\) However, the implications of these variations may be limited as these factors tend to remain stable between the two time points of measuring and we correlated outcome to the relative and not the absolute change in \( rSO_2 \).

In conclusion, NIRS may offer an effective monitoring tool to exclude a relevant number of patients for shunt use during carotid intervention under general anesthesia. Moreover, to selectively indicate the individual patient that needs a shunt NIRS may be useful, but further research is needed before the optimal threshold can be determined and NIRS can be implemented as single cerebral monitoring tool in clinical practice.

**CONFLICT OF INTEREST**

None.

**FUNDING**

None.

**ACKNOWLEDGEMENTS**

We would like to thank Dr. C.H. Ferrier and Mr. D.J. Van Vriesland of the Department of Clinical Neurophysiology for their contribution and specialized assistance. The Invos Cerebral Oximeter (Somanetics Corporation, Troy, MI) was provided free of charge for the duration of the study by Covidien Nederland B.V., Zaltbommel, The Netherlands. However, Covidien had no influence on decisions concerning the study design, on the enrollment of patients, on the collection, analysis, and interpretation of data, on the writing of the report, or on the decision to submit the paper for publication.

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