Cerebral oximetry does not correlate with electroencephalography and somatosensory evoked potentials in determining the need for shunting during carotid endarterectomy

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Objective: Several reports in the literature have described the value of regional cerebral oximetry (rSO_2) as a neuromonitoring device during carotid endarterectomy (CEA). The use of rSO_2 is enticing because it is simpler and less expensive than other neuromonitoring modalities. This study was performed to compare the efficacy of rSO_2 with electroencephalography (EEG) and median nerve somatosensory evoked potentials (SSEP) in determining when to place a shunt during CEA.

Methods: From October 2000 to June 2006, 323 CEAs were performed under general anesthesia by six surgeons. Shunting was done selectively on the basis of EEG and SSEP monitoring under the auspices of an intraoperative neurophysiologist. All patients were retrospectively reviewed to see if significant discrepancies existed between EEG/SSEP and rSO_2.

Results: Twenty-four patients (7.4%) showed significant discrepancies. Sixteen patients showed no significant EEG/SSEP changes, but profound changes occurred in rSO_2, and no shunt was placed. In seven patients there was no change in rSO_2 but a profound change occurred in EEG/SSEP, and shunts were placed. In one patient early in the series, the EEG and SSEP were unchanged but the rSO_2 dropped precipitously, and a shunt was placed. In the 299 patients who showed no discrepancies, 285 were not shunted and 14 required a shunt. Two strokes occurred in the entire series (0.6%), none intraoperatively. Shunts were placed in 23 patients (7%). The sensitivity of rSO_2 compared with EEG/SSEP was 68%, and the specificity was 94%. This gave a positive-predictive value of 47% and a negative-predictive value of 98%.

Conclusions: Relying on rSO_2 alone for selective shunting is potentially dangerous and might have led to intraoperative ischemic strokes in seven patients and the unnecessary use of shunts in at least 16 patients in this series. The use of rSO_2 adds nothing to the information already provided by EEG and SSEP in determining when to place a shunt during CEA. (J Vasc Surg 2008;48:601-6.)

Carotid endarterectomy (CEA) is currently being routinely performed with a perioperative stroke rate of <3%. When large series were first reported in the 1970s, the procedure was performed under general anesthesia with routine shunting.[1,2] Others proposed the use of no shunts.[3] Selective shunting came into favor, because it was recognized that only a small percentage of patients might need a shunt to prevent intraoperative ischemia and because the shunt itself might lead to an intraoperative stroke.[4,5] CEA under regional anesthesia was proposed as the simplest and the most accurate way to monitor the patient, with shunts being placed only if there was a change in neurologic status.[6,7]

The measurement of the internal carotid artery back pressure, or "stump" pressure, was the first monitoring technique used for selective shunting under general anesthesia.[4] Subsequently, the electroencephalogram (EEG), somatosensory evoked potentials (SSEP), and transcranial Doppler (TCD) were shown to be very effective in predicting the need for a shunt.[8-18] The disadvantage of these last three modalities is their somewhat cumbersome nature, their expense, and the need for a skilled technician/interpreter. It was against this backdrop that regional cerebral oximetry (rSO_2) was proposed as a simple, real-time, inexpensive way to determine the need for a shunt during CEA.[19-24] We have used rSO_2 as part of our neuromonitoring protocol, and this report compares our experience with rSO_2 with that of EEG and SSEP for selective shunting.

MATERIALS AND METHODS

From October 2000 to June 2006, 323 CEAs were performed under general anesthesia by six surgeons. An intraoperative neurophysiologist performed continuous cerebral monitoring using a multimodality protocol involving EEG, median nerve SSEP, TCD, and bilateral rSO_2. A balanced anesthetic regimen was administered, with careful attention paid to maintaining stable anesthetic concentrations and blood pressure at the time of carotid cross-clamping. Anesthesia was typically induced and maintained

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with fentanyl, propofol, and rocuronium bromide, as well as a maintenance inhalational agent (isoflurane or sevoflurane).

The Epoch (AXON Inc, Hauppague, NY) or the Cascade (Cadwell Laboratories Inc, Kennick, Wash) were used to simultaneously record EEG and SSEP, which were continuously monitored. For EEG monitoring, four channels of analog and computer-processed waveforms were recorded using the following montage: F3-C3′, C3′-M1, F4-C4′, and C4′-M2. In addition, computer-processed EEG was displayed as a dot-density spectral array with relative brainpower for the traditional EEG bandwidths for alpha, beta, theta, and delta.

For SSEP monitoring, interleaving stimulation of the median nerve at each wrist was delivered using standard stimulating procedures (rate: 4.13 or 4.7 Hz; intensity: 2× the motor threshold; duration: 0.3 milliseconds). For each arm, recording electrodes were placed for three channels: (1) a cervical channel (C2S-Fz), (2) a contralateral cortical channel (C3′-Fz or C4′-Fz), and (3) a cortical-to-cortical channel (C3′-C4′ or C4′-C3′).

TCD monitoring involved placing a 2-MHz probe over the temporal window to insonate the M1 segment of the middle cerebral artery (MCA) on the operative side using either the Neuroguard (Medasonics, Fremont, Calif) or the EME Pioneer (Nicolet Biomedical, Madison, Wisc). Peak systolic and mean blood flow velocities (cm/s) were continuously monitored.

The INVOS Cerebral Oximeter (Somanetics, Inc, Troy, Mich), which uses near infrared spectroscopy, was used to measure rSO_2. Two stick-on sensors were symmetrically placed on the right and left forehead for bilateral recordings. Each housed a near infrared light transmitter and two detectors located 30 and 40 mm from the transmitter. The detector nearest the transmitter received light predominantly from extracerebral tissues (scalp, skull, superficial brain tissue), whereas the more distant detector sampled reflected signals from a deeper area of the brain. For calculation of cerebral oxygenation, the cerebral oximeter algorithm subtracted the reflected signals of the shallow detector from those of the deep detector. Because 75% of the blood volume in the tissue beds is in the venous circulation, the cerebral oximetry index measured cerebral venous oxygenation as a difference in the optical absorption spectra between oxygenated and total hemoglobin.

The setup cost of the neuromonitoring system was $45,000 for the EEG/SSEP, $45,000 for the TCD, and $10,000 for the rSO_2 equipment. Unfortunately, obtaining accurate figures from the hospital for charges, reimbursement, and cost for the various monitoring modes was virtually impossible. The time needed to apply the EEG/SSEP electrodes to the patient was approximately 20 minutes, with an additional 15 minutes for TCD insonation and 2 minutes needed for rSO_2 sensor application.

A profound ischemic event was defined by well-established alarm criteria for the various neuromonitoring modalities.[25] If there was a >50% decrease in amplitude and frequency content of the analog EEG or a significant slowing in the alpha and beta frequencies after cross-clamping of the internal carotid artery, a critical ischemic event was indicated. The alarm criterion for the SSEP was the conventional "50/10 rule". A major ischemic change was defined as a >50% attenuation of the peak-to-trough amplitudes or >10% prolongation in latencies of the N20/P25 complex, or both. For TCD, severe ischemia was defined as a drop in MCA velocity >85% from stable, baseline values. Multiple alarm criteria for rSO_2 were considered: (1) a drop of 10 index points from a stable, trended baseline, (2) a decrease below an absolute value of 50, (3) a relative decrease of 20% to 25%, and (4) an interhemispheric difference of >25%. The four alarm criteria carried equal weight, and the presence of one criterion was enough to declare severe ischemia.

Shunt use was determined by the onset of alarm criteria for either EEG or SSEP after cross-clamping. TCD was used as an adjunct when a temporal window could be obtained. Critical TCD changes did not automatically translate into placement of a shunt if no critical changes occurred in the EEG and SSEP. Mean arterial blood pressure for this study was typically maintained between 90 and 100 mm Hg during crossclamping. If there were mild changes in EEG or SSEP with test clamping, an attempt was made to raise the blood pressure to a maximum of 20% over the awake baseline (most often with phenylephrine) to avoid shunt placement. If the changes did not improve, a shunt was placed.

Selective shunting and conventional CEA technique were used in all patients, with arteriotomy closure at the discretion of the surgeon. Patients were carefully monitored for neurologic changes postoperatively, and most were discharged the next day. The neuromonitoring and hospital records of all patients were retrospectively reviewed.

RESULTS

When the internal carotid artery was clamped, significant discrepancies were seen between rSO_2 and EEG/SEP in 24 of 323 patients (7.4%), consisting of 13 men and 11 women with an average age of 69 years (range, 47-89 years). Five of these 24 patients (21%) were symptomatic. Carotid cross-clamp time during CEA was a mean of 37 minutes (range, 21-69 minutes). Twenty-two arteries were patched—8 with polytetrafluoroethylene, 7 with bovine pericardium, 6 with Dacron, and 1 with autogenous vein—and 2 were closed primarily.

In seven patients there was no change in rSO_2 with clamping. However, alarm criteria were met in both SSEP and EEG in three patients, in EEG alone in three patients, and in the EEG in the only patient where SSEP was not available. TCD monitoring was possible in four of these patients: cerebral blood flow velocity was curtailed in one patient and was nonmeasurable with clamping in three others. Shunts were placed in all seven patients (Table I).

In 16 patients there were critical changes in rSO_2 with clamping, but no significant EEG or SSEP changes. TCD monitoring was possible in 13 of these patients, and an 85%

Table I. Shunt patients

	Critical changes			
Patient	EEG	SSEP	rSO_2	TCD
1	Yes	N/A	No	Yes
2	Yes	Yes	No	Yes
3	Yes	No	No	Yes
4	Yes	Yes	No	Yes
5	Yes	Yes	No	Yes
6	Yes	No	No	Yes
7	Yes	Yes	No	N/A
8	No	No	Yes	Yes

EEG, Electroencephalogram; *N/A,* not available; *SSEP,* somatosensory evoked potentials; *rSO_2,* regional cerebral oximetry; *TCD,* transcranial Doppler.

Table II. Nonshunt patients

	Critical changes			
Patient	EEG	SSEP	rSO_2	TCD
9	No	No	Yes	N/A
10	No	No	Yes	N/A
11	No	No	Yes	N/A
12	No	No	Yes	No
13	No	No	Yes	No
14	No	No	Yes	No
15	No	No	Yes	No
16	No	No	Yes	No
17	No	No	Yes	No
18	No	No	Yes	No
19	No	No	Yes	No
20	No	No	Yes	Yes
21	No	No	Yes	Yes
22	No	No	Yes	Yes
23	No	No	Yes	Yes
24	No	No	Yes	Yes

EEG, Electroencephalogram; *N/A,* not available; *SSEP,* somatosensory evoked potentials; *rSO_2,* regional cerebral oximetry; *TCD,* transcranial Doppler.

drop, or more, in velocity was noted in five. No shunts were placed in any patient (Table II).

In one patient early in the series, the rSO_2 dropped precipitously with clamping, but the EEG and SSEP were unchanged (Table I). Because of our limited experience with rSO_2 at the time and the fact that the TCD showed no measurable flow velocity, a shunt was placed. Later in our experience, there were five more such patients (as noted above) with critical changes only in rSO_2 and TCD in whom the surgeon elected not to place a shunt, and there were no sequelae.

There were no intraoperative strokes, but a postoperative stroke did occur in one asymptomatic patient in the nonshunted group approximately 36 hours after CEA. She had had a lacunar infarction several years before surgery and was hypertensive postoperatively. When she was first noted to have left arm weakness, the results of the computed tomography (CT) and carotid duplex scans were unremarkable. It was surmised that the patient had either had another lacunar infarction or an embolic event from the CEA site.

In the remaining 299 CEA patients, in whom there was no discrepancy between EEG or SSEP and rSO_2, the demographics, clamp times, and methods of arteriotomy closure were essentially the same as the 24 patients who exhibited a monitoring discrepancy. During cross-clamping, 284 patients (95%) showed no changes in EEG/SSEP and rSO_2 and were not shunted, and 15 (5%) showed alarm criteria in EEG or SSEP, or both, and rSO_2 and all were shunted. In one patient the EEG showed no change, but the SSEP and rSO_2 showed alarm criteria. In four other patients the EEG and rSO_2 showed alarm criteria, but the SSEP did not.

Regarding the TCD results in this patient cohort, 18 patients were impossible to monitor (no temporal window). Correlation with the other three monitoring modalities was achieved in 278 patients, but three did not correlate. In one of these last three patients, the TCD showed an alarm value while the other modalities did not. In the other two patients, the TCD did not show alarm criteria and the others did.

No intraoperative strokes occurred, but one asymptomatic nonshunted patient was readmitted for a stroke on postoperative day 4. A carotid duplex scan showed a mobile plaque with thrombus, and an interposition graft was urgently performed. CT scan ultimately showed an infarct in the distribution of the MCA.

In the entire series, two strokes (0.6%) occurred, and shunts were used in 23 patients (7%). The sensitivity of rSO_2 compared with EEG/SSEP was 68%, with a specificity of 94%. This gave a negative-predictive value of 98%, a positive-predictive value of 47%, and an overall accuracy of 93%. TCD monitoring was possible in 301 of 323 patients (93%). The sensitivity of TCD compared with EEG/SSEP was 75%, with a specificity of 98%. This gave a negative-predictive value of 99%, a positive-predictive value of 46%, and an overall accuracy of 97%.

DISCUSSION

CEA can be performed with stroke rates of <3% using shunts routinely, selectively, or not at all. The anesthesia preference of the surgeon and the comfort with use of a shunt determine the conduct of the operation. When CEA was first popularized in the 1970s by Thompson and Javid, they advocated routine shunting under general anesthesia.[1,2] This continues to be the way many surgeons perform this operation.[26] Baker et al,[3] by contrast, used no shunts in a large series because of concerns about embolization or intimal injury from the shunt. Others continue to perform CEA routinely under general anesthesia without shunts.[27]

Reflecting the view of surgeons who prefer to shunt selectively, Ahn stated, "Approximately 10% to 15% of patients who undergo CEA need a temporary indwelling shunt to maintain adequate cerebral blood flow during carotid artery crossclamping. There is no need to subject the other 85% to 90% of patients who undergo CEA the

Table III. Comparisons between regional cerebral oximetry and other neuromonitoring modalities

First author	*Modality*	*Patients, No.*	*Δ rSO_2, %*	*Sensitivity, %*	*Specificity, %*
De Letter[35]	EEG	102	5	100	44
Beese[36]	SSEP	317	5	76	64
Grubhofer[37]	TCD	55	13	100	87
Samra[38]	Awake/neuro exam	94	20	80	82
Rigamonti[39]	Awake/neuro exam	50	15	44	82

EEG, Electroencephalogram; *N/A,* not available; *SSEP,* somatosensory evoked potentials; *rSO_2,* regional cerebral oximetry; *TCD,* transcranial Doppler.

unnecessary risk and encumbrance associated with a shunt."[28]

The concerns are complications from shunt insertion—emboli or intimal injury—and possible compromise of the technical performance of the operation, such as lack of visualization of the distal plaque end point. Sundt et al[29] found that the risk of distal embolization with a shunt was 0.5%. Green et al[30] described difficulty with insertion of the shunt as the cause of stroke in two patients in their series. In one patient plaque embolized through the shunt, and in the other patient the shunt injured the distal internal carotid artery. More important, in patients in whom a shunt was placed, there was a statistically significant increase in the number of strokes due to technical error.

The simplest way to selectively use a shunt is to monitor the neurologic status of the patient under regional anesthesia, shunting only when a change is noted.[6-7,31] However, the success of this technique is critically dependent on a cooperative patient, the appropriate level of sedation, and the quality of the regional block. Under general anesthesia, stump pressure measurement, pioneered by Moore, was considered a simple and inexpensive way to determine the need for a shunt.[5] The disadvantages were its "snap-shot" nature and the lack of agreement on a critical stump pressure.[9,32] With the advent of more sophisticated neuromonitoring, the use of stump pressures is now far less common.[33]

Sundt et al[8] ushered in the current era of neuromonitoring under general anesthesia when they showed the correlation between significant EEG changes and a cerebral blood flow of $\leq$15 mL/100 g/min.[8] In their series of 1145 consecutive CEAs, no patient emerged from anesthesia with a new deficit that was not predicted by the intraoperative EEG. Excellent CEA results have been obtained by others as well by using selective shunting determined by EEG under general anesthesia.[9-11] SSEP has similarly been found to be highly reliable in determining the need to shunt.[12-14] A review of 994 carotid reconstructions found only one patient where neurologic complications ensued without a critical change in SSEP.[13] In fact, EEG and SSEP may be complementary when used together and may evaluate different regions of the brain. Although EEG may more quickly demonstrate severe hypoperfusion, SSEP changes may precede EEG changes when the onset of cerebral ischemia is more gradual.[14,25,34] The disadvantages of these two techniques are the cost, setup, equipment, and the need for a neurophysiologist.

In an effort to simplify neuromonitoring for CEA under general anesthesia, rSO_2 was proposed. Reports with a limited number of patients have shown an appropriate drop in rSO_2 values with carotid cross-clamping[19] and restoration to baseline with subsequent shunt insertion.[20] Other limited reports have favorably compared rSO_2 with stump pressures,[21] SSEP,[22] and TCD.[23,24] However, none of these study authors were willing to comment on an absolute threshold value or a change in rSO_2 from baseline that would be an alarm criteria for shunting.

A number of larger series have cast considerable doubt on the value of rSO_2 when comparing it with other neuromonitoring modalities for CEA patients under general anesthesia (Table III)[35-39]:

- De Letter et al[35] compared EEG with rSO_2 in 102 patients. The EEG alarm criteria for shunting correlated with a 5% decrease in rSO_2 from baseline and gave a sensitivity of 100%; however, the specificity at this value was only 44%.
- Beese et al[36] compared SSEP with rSO_2 in 317 CEA patients using SSEP alarm criteria for shunting. Because of substantial interindividual variability, no critical change in rSO_2 could be defined that could identify patients with clinically significant SSEP changes who would benefit from shunt placement. As the decrease in rSO_2 from baseline grew, the specificity approached 100%, but the sensitivity dropped precipitously. As a consequence, the authors recommended not using rSO_2 for the detection of cerebral ischemia during CEA.
- Grubhofer et al[37] compared TCD with rSO_2 in 55 CEA patients. A 13% decrease in the rSO_2 baseline correctly identified all patients requiring a shunt by the standard TCD alarm criteria. However, if the decision for shunting had been determined only by rSO_2 values, the specificity of 87% would have led to unnecessary shunting in 13% of patients.

Two reports studied rSO_2 monitoring in patients undergoing CEA with regional anesthesia. Samra et al[38] reviewed 94 such patients where the decision to place a shunt was made exclusively by the neurologic status of the patient. In the 10 patients who showed clinical signs of cerebral ischemia, a 20% decrease in rSO_2 gave the best sensitivity (80%) and specificity (82%). The false-positive rate for this cutoff value was 66.7%, with a false-negative rate of 2.6%. These authors concluded that it was not possible to specify an absolute decrease in rSO_2 that would predict cerebral ischemia.

Finally, Rigamonti et al[39] reported 50 similar patients where EEG and rSO_2 were continuously monitored. Five patients required a shunt because of severe cerebral ischemia documented by clinical examination and EEG. With carotid clamping, rSO_2 values did drop, but no absolute decrease in rSO_2 value from baseline was found that could, by itself, predict the need for a shunt. A drop in rSO_2 of ≥15% during clamping gave the highest specificity (82%) and sensitivity (44%) in the study.

A key issue in this study is that we consider EEG/SSEP the standard against which rSO_2 is compared.[25,34] Two of the previously discussed rSO_2 reports used EEG/SSEP in their comparisons as well.[35,36] Confusion arises with studies that monitor awake CEA patients with simultaneous neurologic examination and EEG. Hans and Jareunpoon[40] showed a high false-negative rate for EEG in their study. This is most likely because the neurologic changes are rapid, whereas EEG changes can be more gradual and do not show up by the time the shunt is placed. These comparisons are also problematic because the EEG of a patient who is awake is not the same as an EEG of a patient under general anesthesia. For the purposes of this study, we believe that there is a sufficient body of evidence to show that EEG/SSEP are currently the best neuromonitoring modalities available for CEA patients under general anesthesia.[8-14,16-18,25,34]

An interesting finding in this study is the discrepancies between TCD and EEG/SSEP. In the subset of six patients who had no EEG/SSEP changes but alarm criteria changes on TCD and rSO_2, a shunt was placed in only one, early in the series, because of inexperience with rSO_2. All patients did well. There are two possible explanations for this TCD discrepancy. First, if the velocity tracings become flat with clamping of the internal carotid artery, it suggests that the carotid siphon is being insonated rather than the MCA, and flow in the siphon virtually stops. Second, if there is a >85% drop in flow velocity without a completely flat tracing but no alarm criteria change in EEG/SSEP, it would appear that the collateral flow is sufficient to maintain adequate brain perfusion. Diminished MCA perfusion could also explain the critical changes in rSO_2 with crossclamping. In fact, the sensitivities and the positive-predictive values for TCD and rSO_2 were very similar in this study.

It may be presumptive to suspect that events might have been different had shunts not been placed in the seven patients with no rSO_2 changes in the face of alarm criteria changes in EEG or SSEP, or both. However, a review of the reports of CEAs done without use of a shunt is instructive. Baker et al[3] recommended, in hindsight, that shunts be considered in patients with a contralateral carotid occlusion and a stump pressure of <50 mm Hg, because this subgroup was at a higher risk for intraoperative hypoperfusion during cross-clamping. Also, both Baker et al[3] and Samson et al[27] closed most of their arteriotomies primarily, making the cross-clamp time (and thus the ischemia time) much shorter than that for a patch closure. Five patients (0.8%) in the Samson et al[27] series awoke with a fixed neurologic deficit, suggesting that poor cerebral perfusion during CEA could have been responsible for some of these strokes. Finally, using cerebral blood flow studies during CEA, Sundt et al[29] believed that 12% of their patients would have sustained a major cerebral infarction if the cross-clamp time had extended for as long as 20 minutes without cerebral protection. For all of these reasons, and given our results and those of others, we continue to believe that selective shunting under general anesthesia with EEG/SSEP monitoring is appropriate. The low 7% rate of shunt use in this series may be a tribute to our outstanding neurophysiologists who, among many other things, work with the anesthesia staff to safely maximize blood pressure during cross-clamp.

CONCLUSION

To our knowledge, this study is currently the largest collection of CEA cases reported comparing rSO_2 with other neuromonitoring modalities. Our results show that relying on rSO_2 alone for shunting is potentially dangerous and might have led to intraoperative ischemic strokes in seven patients and the unnecessary use of shunts in at least 16. This lack of correlation between rSO_2 and EEG/SSEP is in keeping with previous reports. The use of rSO_2 adds nothing to the information already provided by EEG, SSEP, and TCD during CEA, and in its current state, rSO_2 cannot be recommended as the sole means of determining when to place a shunt.

AUTHOR CONTRIBUTIONS

Conception and design: MF, MI
Analysis and interpretation: MF, MI
Data collection: JC, DG
Writing the article: MF
Critical revision of the article: MF
Final approval of the article: MF
Statistical analysis: MF
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