Prospective evaluation of electroencephalography, carotid artery stump pressure, and neurologic changes during 314 consecutive carotid endarterectomies performed in awake patients

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Objective: **This study attempted to correlate neurologic changes in awake patients undergoing carotid endarterectomy (CEA) under cervical block anesthesia (CBA) with electroencephalography (EEG) and measurement of carotid artery stump pressure (SP).**

Methods: **Continuous EEG and SP monitoring was measured prospectively in 314 consecutive patients undergoing CEA between April 1, 2003, and July 30, 2006, under CBA. Indications for CEA were asymptomatic 70% to 99% internal carotid artery stenosis in 242 (77.1%), transient ischemic attacks (including transient monocular blindness) in 45 (14.3%), and prior stroke in 27 (8.6%). Mean common carotid artery pressure before clamping, mean SP after carotid clamping, and intraarterial pressure were continuously monitored in all patients. An indwelling shunt was placed when neurologic events (contralateral motor weakness, aphasia, loss of consciousness, or seizures) occurred, regardless of SP or EEG changes.**

Results: **Shunt placement was necessary because of neurologic changes in 10% (32/314) of all CEAs performed under CBA. Only 3 patients (1.4%) of 216 required shunt placement if SP was 50 mm Hg or more, vs 29 (29.6%) of 98 if SP was less than 50 mm Hg (*P* < .00001; sensitivity, 29.8%; specificity, 98.6%). In patients with SP of 40 mm Hg or more, 7 (2.6%) of 270 required shunt placement, vs 25 (56.8%) of 44 if SP was less than 40 mm Hg (*P* < .00001; sensitivity, 56.8%; specificity, 97.4%). Ischemic EEG changes were observed in 19 (59.4%) of 32 patients (false-negative rate, 40.6%) requiring shunt placement under CBA. Three patients had false-positive EEG results and did not require shunt placement (false-positive rate, 1.0%). The perioperative stroke/death rate was 4 (1.2%) in 314. All strokes occurred after surgery and were unrelated to cerebral ischemia or lack of shunt placement.**

Conclusions: **Ten percent of patients required a shunt placement during CEA under CBA. Shunt placement was necessary in 56.8% of patients with SP less than 40 mm Hg. EEG identified cerebral ischemia in only 59.4% of patients needing shunt placement, with a false-positive rate of 1.0% and a false-negative rate of 40.6%. Both SP and EEG as a guide to shunt placement have poor sensitivity. Intraoperative monitoring of the awake patients under regional anesthesia (CBA) is the most sensitive and specific method to identify patients requiring shunt placement. (J Vasc Surg 2007;45:511-5.)**

Cerebral ischemia and infarction during carotid cross-clamping are well-recognized hazards of carotid endarterectomy (CEA). Optimal methods of detection of cerebral ischemia during CEA remain controversial. The adequacy of collateral cerebral circulation and the need for intraoperative shunt placement can be assessed by continuous electroencephalographic (EEG) monitoring, measurement of carotid artery stump pressure (SP), or performance of CEA under cervical block anesthesia (CBA) in the awake patient.[1-21] According to retrospective case studies, continuous intraoperative EEG monitoring is an extremely sensitive indicator of cerebral ischemia under general anesthesia (GA).[3,7,9,13,18] There are only two reported prospective studies of EEG monitoring in a small number of patients undergoing CEA under CBA.[5,16] The optimal SP value above which it is safe not to perform shunt placement has been reported to vary from 35 to 50 mm Hg,[2,8,10,11,13] with one study reporting a low value of 25 mm Hg.[1] Because of a wide range of optimal SP readings and a relative paucity of EEG data in a large cohort, a prospective evaluation of 314 CEAs under CBA with measurement of SP and continuous EEG monitoring is reported.

METHODS

Continuous EEG and SP monitoring was performed prospectively in 314 consecutive patients undergoing CEA from April 1, 2003, to July 30, 2006, under CBA at St John Macomb Hospital (Warren, Mich) and St Joseph Hospital (Clinton Township, Mich)—both 300-bed suburban teaching hospitals. Indications for CEA were asymptomatic 70% to 99% internal carotid artery (ICA) stenosis in 242 (77.1%), transient ischemic attack symptoms (including transient monocular blindness) in 45 (14.3%), and stroke in 27 (8.6%). The mean age was 71.9 years (range, 48-90 years), with 181 male patients and 133 female patients. Risk

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factors for carotid stenosis included coronary artery disease in 193 patients, hypertension in 273, diabetes mellitus in 83, chronic obstructive pulmonary disease in 34, and dyslipidemia in 241. Primary CEA was performed in 282 patients, with primary closure in 87, patch graft closure in 187, and eversion endarterectomy in 8. Redo CEA was performed in 32 patients, including 12 carotid interposition graft procedures. During the same period, 33 patients underwent CEA under GA because of extreme anxiety/claustrophobia, combined coronary artery bypass grafting and CEA, deafness, and inability to communicate in the English language. After carotid duplex study, 158 patients underwent intraarterial digital subtraction arteriography of the carotid and arch vessels, 120 underwent magnetic resonance angiography of the carotid arteries, and 31 underwent computed tomographic angiography of the carotid arteries. Five patients had CEA on the basis of carotid duplex study only. Data were entered prospectively in the computerized registry (Microsoft Excel; Microsoft, Redmond, Wash). All operations were performed by one surgeon (S.S.H.). All 314 patients underwent intra-arterial pressure monitoring (radial artery pressure in 309 and brachial artery pressure in 5) for systemic pressure monitoring. After systemic heparin administration, a 19-gauge needle was inserted into the distal common carotid artery (CCA), and the external carotid artery was clamped. The mean CCA pressure was recorded after equilibration, and three readings were taken; the mean of these three readings is presented. After measurement of the mean CCA pressure, the clamp was applied proximal to the site of the insertion of the needle into the CCA, and a mean SP was recorded (the mean of three readings is reported). Mean CCA pressure was determined to correlate mean CCA pressure with intra-arterial pressure. The stump index was calculated by dividing the mean SP by the CCA pressure and multiplied by 100 (SP/CCA × 100). After carotid clamping, neurologic assessment was performed by having patient squeeze the contralateral hand and answer simple commands (speech assessment). Neurologic assessment was continuous throughout the operative procedure. A shunt was placed because of contralateral motor deficit, aphasia, loss of consciousness, or seizure, regardless of changes in EEG or SP readings.

EEG monitoring. Continuous EEG monitoring was performed by placing 16 electrodes affixed with Elefix conductive paste on the scalp by using 16 channels (Cadwell, Kennewick, Wash). These electrodes were placed in the preoperative holding room. EEG was recorded by using a Locut filter of 0.53 Hz and a Hicut filter of 70 Hz. The raw EEG was visualized with a time base of 30 mm/s (speed) and with a gain of 3μV/mm (sensitivity). Additionally, EEG was computationally viewed in the compressed spectral array form with an epoch of 10 seconds. Criteria for a change in EEG were in noticeable slowing of EEG frequency in the alpha and beta frequencies and a 50% reduction in EEG amplitude.

Cervical block anesthesia. CBA was performed by the anesthesiologist in the preoperative holding room after premedication with 1 mg of midazolam. An equal mixture (1:1) of 2% lidocaine hydrochloride (Hospira Inc, Lake Forest, Ill) and 1.5% bupivacaine with epinephrine 1:200,000 (Hospira Inc) was infiltrated: 10 mL as a superficial cervical block and 20 mL as a deep cervical block by using the triple-injection technique with 5 to 7 mL at each level. During the operative procedure, additional infiltration of the same anesthetic mixture was used, but sedation was avoided.

Table I. Probability of shunt placement for stump pressure 50 mm Hg

	Stump pressure <50 mm Hg	*Stump pressure ≥50 mm Hg*
Shunt (n = 32)	29	3
No shunt (n = 282)	69	213
Sensitivity	29.6%	
Specificity	98.6%	
False-positive rate	1.4%	
False-negative rate	70.4%	
Positive predictive value	90.6%	
Negative predictive value	75.5%	

Statistical analysis. Proportions for the different populations (shunt and no shunt; GA and cervical block; EEG normal or abnormal) were compared by using the Fisher exact test. Continuous variables (age and pressures) were evaluated by using the unpaired *t* test. A *P* value <.05 was considered to be significant.

RESULTS

Of the 314 patients in this study who underwent CEA under CBA, an indwelling shunt was used in 32 instances (10%) because of a neurologic deficit after carotid clamping. There was no correlation between the need for shunt placement and indications for CEA (24 patients in the asymptomatic group needed a shunt, as did 6 patients with transient ischemic attack and 2 patients with stroke; $P > .5$). The contralateral ICA was normal or had less than 50% stenosis in 19 patients, had 51% to 69% stenosis in 1, and had 70% to 99% stenosis in 8. The contralateral ICA was occluded in four of 32 patients requiring shunt placement. Of 11 patients with ICA occlusion, 4 required shunt placement (31.6%), compared with 28 (9.2%) of 303 patients without contralateral ICA occlusion ($P = .018$).

Stump pressure. Three of 216 patients had SP of 50 mm Hg or more and required shunt placement because of neurologic changes, compared with 29 of 98 with SP less than 50 mm Hg ($P = .0001$). No patient with SP of 60 mm Hg or greater required shunt placement.

Using 50 mm Hg SP as a threshold for shunt placement, sensitivity was 29.6%, and specificity was 98.6% (Table I). The need for shunt placement was 7 (2.6%) of 270, with a mean SP of at least 40 mm Hg. However, 56.8% of the patients (25/44) required shunt placement with SP of 40 mm Hg or less ($P = .0005$; sensitivity, 56.8%; specificity, 97.4%; Table II). The mean SP in patients (n =

Table II. Probability of shunt placement for stump pressure 40 mm Hg

	Stump pressure <40 mm Hg	*Stump pressure ≥40 mm Hg*
Shunt (n = 32)	25	7
No shunt (n = 282)	19	263
Sensitivity	56.8%	
Specificity	97.4%	
False-positive rate	2.6%	
False-negative rate	43.2%	
Positive predictive value	78.1%	
Negative predictive value	93.3%	

Table III. EEG monitoring and neurologic changes (shunt placement) under cervical block anesthesia

	Shunt placed	*No shunt*
EEG abnormal (n = 22)	19	3
EEG normal (n = 292)	13	279
Sensitivity	59.4%	
Specificity	98.9%	
False-positive rate	1.1%	
False-negative rate	40.6%	
Positive predictive value	86.4%	
Negative predictive value	95.5%	

EEG, Electroencephalography.

32) with shunt placement was 34.8 ± 1.5 mm Hg, compared with 68.1 ± 0.9 mm Hg in the remaining 282 patients without shunt placement ($P < .0005$). The mean stump index was 32.24 ± 8.03 in 32 patients requiring shunt placement, compared with 53.37 ± 12.5 in the remaining group ($P < .0005$).

EEG monitoring. Ischemic EEG changes were observed in 19 (59.4%) of 32 patients requiring shunt placement. Three patients had ischemic EEG findings but no change in neurologic status, and, therefore, a shunt was not placed (false-positive rate, 1.1%). EEG was normal in 13 patients despite neurologic changes with carotid clamping (false-negative rate, 40.6%; Table III). There was no correlation between ischemic EEG findings and SP greater than 40 mm Hg ($P = .648$). Correlation of EEG findings and an SP threshold of 40 mm Hg resulted in a sensitivity of 86.4% and a specificity of 97% (Table IV).

Neurologic events such as contralateral weakness, aphasia, loss of consciousness, and seizures were immediate in 27 patients. However, neurologic deficits developed within 5 to 15 minutes of carotid clamping in the remaining five patients. In one patient, delayed neurologic deficit after carotid clamping (SP, 42 mm Hg) was probably due to overaggressive treatment of intraoperative hypertension, resulting in a decrease of the mean systemic blood pressure from 90 to 50 mm Hg. Another patient (with advanced chronic obstructive pulmonary disease) had an increased

Table IV. Correlation of EEG changes and stump pressure at 40 mm Hg with neurological changes

EEG findings	*Stump pressure <40 mm Hg*	*Stump pressure ≥40 mm Hg*
EEG positive (n = 22)	19	3
EEG negative (n = 292)	3	289
Sensitivity	86.4%	
Specificity	99.0%	
False-positive rate	1.0%	
False-negative rate	13.6%	
Positive predictive value	86.4%	
Negative predictive value	99.0%	

EEG, Electroencephalography.

P_{CO_2} secondary to hypoventilation. This patient had an SP of 54 mm Hg. No obvious cause of delayed neurologic deficit was apparent in the remaining three patients. The cerebral ischemia time during carotid clamping was 41.7 ± 8 minutes.

In this study, 90.2% (314/347) of CEAs were performed under CBA; 33 patients during the same time interval underwent CEA under GA with EEG and somatosensory evoked potential monitoring along with measurement of SP. Four (1.2%) perioperative strokes occurred after 314 CEAs under CBA. One patient with a recent left hemiparesis developed intracerebral hemorrhage 8 hours after CEA and underwent craniotomy but eventually died 3 months later. One of the remaining three patients had a stroke 10 minutes after skin closure, was re-explored, and was found to have dislodgement of plaque from the proximal CCA. This patient developed left hemiparesis with moderate recovery. The remaining two patients had mild neurologic deficits with complete recovery without re-exploration of the carotid artery. Three patients had permanent and cranial nerve palsy (vagus, n = 1; glossopharyngeal, n = 1; hypoglossal, n = 1).

DISCUSSION

Monitoring of neurologic function in awake patients undergoing CEA provides a reliable indicator for placement of a shunt during the period of carotid cross-clamping. Although many studies have shown satisfactory outcomes of CEA under GA with routine use of shunts, shunt-related complications may negate the benefits of cerebral protection.[1-5,7] Green et al[7] reported that technical problems were more common when shunts were used (5%) than when they were not (0.9%). In this study, 32 (10%) of 314 patients developed cerebral ischemia (neurologic deficit) during carotid clamping under CBA. There results are similar to those reported by Evans et al[5] (9.7%), Calligaro and Dougherty[20] (7.2%), Stroughton et al[16] (14%), and Rockman et al[14] (11%) for CEA in awake patients.

Our data are in accordance with other reported series that the severity of the contralateral ICA stenosis or the indications for CEA will not determine the need for a shunt in a patient.[5,8,10] However, patients undergoing CEA in the presence of contralateral ICA occlusion required a shunt three times more often than those without ICA occlusion—a finding similar to that reported by other investigators.[8,9,18]

Some investigators routinely place shunts for cerebral protection in patients with a history of stroke undergoing CEA.[14,20] Asymptomatic patients may be able to tolerate a period of ischemia with loss of electric function but without any structural changes in the brain. However, patients with prior infarction (stroke) are more susceptible to low flows and require high perfusion pressure to prevent further structural damage.[7]

In this study, shunts were placed only on the basis of neurologic changes during carotid clamping irrespective of the preoperative neurologic symptoms. Only 2 of 27 patients undergoing CEA for stroke required shunt placement (8.6%), an incidence similar to that of the asymptomatic and transient ischemic attack group (30 of 287; 10.4%; $P > .05$).

The optimal SP value above which it is safe not to place a shunt is controversial because reported series have a wide range of SP (from 25 to 50 mm Hg). Some series have reported mean and others have reported systolic SP for evaluation of adequate cerebral collateral flow.[1-3,6,11,15,16] Because the difference between systolic and diastolic SP is small, mean SP was used in this study. Moore and Hall[1] concluded that carotid clamping could be safely tolerated when mean SP was greater than 25 mm Hg. McCarthy et al[13] and Hays et al[2] reported an optimal value of SP of 35 and 40 mm Hg, respectively. Ricotta et al[11] determined that the optimal value of SP was 50 mm Hg. Baker et al[4] reported an intriguing study of 940 patients undergoing CEA under GA without shunt placement. They reported a stroke rate of 1.1% in patients with SP greater than 50 mm Hg and 4.7% for SP less than 40 mm Hg.[4]

Hafner and Evans[8] and Evans et al[5] reported that no patient with SP greater than 50 mm Hg developed a neurologic deficit after carotid clamping under local infiltration anesthesia. However, Calligaro and Dougherty[20] observed neurologic deficits in 3 of 335 patients with a SP greater than 50 mm Hg under CBA. Three of 216 patients in this series with SP greater than 50 mm Hg developed neurologic changes after carotid clamping. We are not certain that these findings can be extrapolated to patients undergoing CEA under GA because some GA agents are neuroprotective. It is possible that the patients ($n = 3$) with high SP (>50 mm Hg) who developed neurologic changes under CBA may not have developed stroke after CEA without a shunt, because cerebral ischemic changes may be reversible with re-establishment of cerebral blood flow. No patient in this report with SP greater than 60 mm Hg developed a neurologic deficit after carotid clamping.

Reported studies pertaining to EEG monitoring during CEA under GA are largely based on retrospective analysis. The incidence of ischemic EEG in patients undergoing CEA under GA is reported to vary from 12% to 18%.[3,7,9,13,18] Under GA, EEG is considered to be a highly sensitive method of monitoring cerebral perfusion.[18,19] However, interpretation of intraoperative EEG is complicated by focal EEG abnormalities that may persist during the monitoring in patients with preoperative neurologic deficits, changes in the concentration of anesthetic agents and Pa_{CO_2}, and severe hypotension.[7,18,19] An ideal method of cerebral monitoring should not miss any patient requiring shunt placement (0% false-negative rate). Although Schneider et al[18] and Ricotta et al[11] have reported a 0% false-negative rate with EEG monitoring, Green et al,[7] McCarthy et al,[13] and Kresowik et al[9] have reported false-negative rates of 0.7%, 1.4%, and 2.6%, respectively, with GA.

EEG was normal in 13 of 32 patients requiring shunt placement in this series (sensitivity, 59.4%; false-negative rate, 40.6%). Evans et al[5] reported the EEG to be 69% sensitive and 89% specific for neurologic changes in 134 awake patients undergoing CEA, whereas Stroughton et al[16] evaluated EEG in 89 patients undergoing CEA under CBA and reported a sensitivity of 73% and a specificity of 92%. However, Evans et al[5] and Stroughton et al[16] reported a false-negative rate of 3.7% and 4.5%, respectively, in awake patients. The sensitivity and specificity of EEG in this study were similar to those in the aforementioned studies, but we detected a much higher false-negative rate with the EEG (40.6%). The sensitivity of EEG was 86.4% in patients with SP less than 40 mm Hg. Three patients with ischemic EEG but without any change in neurologic status did not undergo shunt placement (false-positive rate, 1%). All three patients had SP less than 40 mm Hg. It is conceivable that EEG changes under CBA may not be similar to EEG changes under GA.[17] Neurological deficits developed rapidly (within 60 to 90 seconds) in patients after carotid clamping under CBA, so immediate insertion of the shunt may have prevented development of EEG changes. It has also been reported that in some patients, slow onset of cerebral ischemia may not result in detectable EEG changes.[21] This may partially explain the high false-negative rate (40.6%) of the EEG in this series. We cannot explain the reasons for the false-positive EEG changes.

A cerebral blood flow rate of less than 10 mL/100 g per minute usually provides rapid EEG changes.[19] According to Sundt et al,[19] some patients with a flow rate of 10 to 18 mL/100 g per minute may not have immediate EEG changes, but if ischemia is allowed to persist, EEG changes will develop in most such patients. Because the number of patients undergoing CEA for symptoms of stroke (7.8%) was relatively small, recommendations regarding SP and EEG criteria for shunt placement cannot be made with certainty from the results of this study. Ten percent of patients required shunt placement under CBA. Shunt placement was necessary in 56.8% of patients with SP less than 40 mm Hg. EEG identified cerebral ischemia in only 59.4% of patients needing shunt placement. Negative EEG (no ischemic changes) or high SP (>50 mm Hg) measurement will not identify all patients requiring shunt placement undergoing CEA while awake.

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AUTHOR CONTRIBUTIONS

Conception and design: SSH, OJ
Analysis and interpretation: SSH
Data collection: SSH, OJ
Writing the article: SSH
Critical revision of the article: SSH
Final approval of the article: SSH
Statistical analysis: SSH
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