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Carotid Endarterectomy

Lessons from Intraoperative Monitoring—A Decade of Experience

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Objective

The authors analyzed a single institution's 10-year experience with intraoperative monitoring during 709 primary carotid endarterectomies and investigated the impact of contralateral internal carotid artery stenosis on carotid artery stump pressure (SP).

Summary Background Data

Stump pressure reflects the combination of contralateral carotid artery anatomy, collateral intracranial vasculature, and systemic blood pressure. By controlling for blood pressure with a stump index (SI) (SI = [SP/mean arterial pressure] × 100), a correlation between pressure and contralateral carotid artery anatomy can be demonstrated. Although the use of SP has long been advocated as an indicator of adequate cerebral perfusion, its correlation with perioperative complications while using an intraluminal shunt has not been evaluated completely.

Methods

From a series of 886 primary carotid endarterectomy cases, SP and mean arterial pressure were measured prospectively in 709 procedures. Temporary intraluminal shunts were used in cases with demonstrated contralateral carotid occlusion, prior cerebrovascular accident (CVA), or SPs less than 35 mmHg. Ipsilateral and contralateral angiographic degree of carotid stenosis was recorded at the time of the operation. Neurologic status was recorded prospectively for all 709 procedures. Operative electroencephalogram (EEG) changes and SP then were compared with the neurologic status of the patient in the perioperative period.

Results

The mean SP for the group ($n = 709$) was 46.7 ± 15.3 mmHg (mean ± standard deviation [SD]) with a mean SI of 54.9 ± 22.6. The distribution for the SI is a more gaussian curve than that for SP. There were 19 ipsilateral CVAs (2.7%). The mean SP in the nonstroke group was 47.1 ± 15.2 mmHg (mean SI = 54.7 ± 16.5) compared with 31.9 ± 13.2 mmHg (mean SI = 38.8 ± 18.2) in the stroke group ($p < 0.0001$). Stroke rate for SP ≤ 35 mmHg was 7% (13/185) *versus* 1.1% (6/524) for SP > 35 ($p < 0.0001$). Stump index and SP are related to contralateral carotid artery stenosis. The pattern of SI or SP *versus* contralateral stenosis is biphasic, with an increase at 75%. If SI is ≤ 40, the mean contralateral stenosis is 55.1%; if SI is > 40, the mean contralateral stenosis is 35.1% ($p < 0.05$). Continuous EEG monitoring was completed for the 549 most recent operations. Patients who had a perioperative stroke had EEG changes observed during the procedure in only 6 of 12 cases (50% sensitivity), with 76% specificity. Using SP ≤ 35 mmHg, sensitivity was 68% and specificity was 75%.

Conclusion
Low SPs are associated with perioperative stroke despite the use of shunts. This trend accelerates when SP ≤ 35 mmHg. There is an inverse correlation between contralateral carotid stenosis and SI or SP. A slight increase in pressure with contralateral stenosis greater than 50% may reflect increased collateral development secondary to chronic hypoperfusion. Stump pressure sensitivity is a better indicator of perioperative stroke than EEG monitoring, with a similar specificity.

Recent randomized, prospective trials have demonstrated the superiority of carotid endarterectomy compared with the best medical treatment for both asymptomatic and symptomatic patients with extracranial carotid artery disease.[1,2] These studies have proven the benefit of carotid endarterectomy, assuming a low rate of morbidity and mortality. One important variable in achieving this efficacy is the effective intraoperative monitoring of patients to identify and appropriately manage cerebral ischemia during carotid cross-clamping.

Since the inception of carotid endarterectomy for the treatment of cerebrovascular disease, technical aspects of the operative method have remained relatively unchanged.[3,4] However, one area of active debate has been the choice of monitoring techniques to direct intraoperative management and decision making. In the past, various methods have been proposed to evaluate the patient's cerebral perfusion while the carotid artery is cross-clamped. Currently, the three most widely used techniques include local or regional anesthesia with upper extremity function monitoring,[5,6] continuous electroencephalogram (EEG) monitoring,[7–10] and stump pressure (SP) measurements.[11–13] The greatest difficulty in contrasting the relative merits of these monitoring techniques is the excellent outcome—thus, few negative endpoints—reported with all three methods. Studies often have failed to demonstrate any trend in the data because of the small number of ischemic events observed in a given series. Additionally, there have been relatively few randomized comparisons of different operative monitoring techniques from a single institution. The different operative monitoring strategies are used primarily to determine the need for a temporary indwelling shunt during the carotid clamp time.

After 40 years of experience with carotid surgery for the secondary prevention of cerebral vascular accidents, the debate on shunting for prophylactic cerebral protection continues to divide surgeons into three differing schools of thought: obligatory shunting, no shunting, and selective shunting. Imparato et al., Thompson and Talkington, and others have advocated routine shunting to maximize protection from cerebral hypoperfusion during every carotid endarterectomy.[14–19] Conversely, Baker has argued that shunts increase operative morbidity by causing technical problems, arterial damage, thrombosis, and embolization.[20] However, Baker has acknowledged the benefit of shunting for some patients at particularly high risk.[21] The use of selective shunting has been supported by Moore et al., dating back to 1969.[11–12] Popularity of selective shunting has been increasing in recent years.[22–24] Similar to the debate for different operative monitoring techniques during surgery, equally acceptable results have been demonstrated by all three approaches to shunting.

The measurement of carotid SP was introduced in 1960 by Crawford et al.[25] Carotid SP is the mean arterial back pressure in the internal carotid artery that has been clamped proximally. Inherent in its origin is the influence of systemic mean arterial pressure (MAP). The stump index (SI) is a measurement of the SP corrected for MAP and expressed as a percentage (SI= [SP/MAP] × 100). By thus standardizing the SP measurements, a correlation to contralateral carotid artery anatomy can be better characterized. The carotid SI was first described by Hafner in 1984 as an additional method of cerebral perfusion assessment.[26] In 1995, Harada et al.[24] evaluated SP and SI in relation to electroencephalographic changes during carotid endarterectomy. Although these studies reported an association between the SP and SI and the changes in EEG, the relationship to perioperative morbidity or mortality was not investigated.

Contralateral internal carotid artery stenosis is an important factor of consideration when performing a carotid endarterectomy. Experience has shown that carotid endarterectomy can be performed with acceptable morbidity and mortality in patients with contralateral carotid artery occlusion.[27] Although many authors have commented on surgical considerations concerning contralateral carotid artery stenosis,[27-31] the contribution of collateral flow from the contralateral carotid circulation has been difficult to analyze quantitatively.

The current study reviews a large series of primary carotid endarterectomies performed at a single institution

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Table 1. CHARACTERISTICS OF OPERATIVE PROCEDURES (N = 709)

All patients (n)	709
Average age (yr) (mean ± SD)	67.3 ± 8.6
Side of operation	
Left	358/709 (50.6%)
Right	351/709 (49.4%)
Gender	
Males	427/709 (60.2%)
Females	282/709 (39.8%)
Comorbidity*	
Hypertension	
+	369 (58%)
−	267 (42%)
Diabetes mellitus	
+	117 (17%)
−	574 (83%)
Smoker	
+	530 (78%)
−	151 (22%)

SD = standard deviation.
* Data not available for all patients.

in which EEG monitoring and SP measurements were performed routinely. Preoperative angiography was used to assess the degree of stenosis of both carotid arteries in all cases. The objective of this study was to correlate the preoperatively determined carotid stenosis, the intraoperative findings, and the perioperative morbidity and mortality.

MATERIALS AND METHODS

All carotid endarterectomy procedures performed by a single group of vascular surgeons at Northwestern Memorial Hospital (Chicago, IL) during a 10-year period from July 1, 1983 to December 31, 1993 were included in this study. Of 886 consecutive carotid endarterectomy procedures, SPs and MAPs were prospectively recorded for 815 operations. Patients with operations for restenosis after previous carotid endarterectomy, combined operations with coronary artery bypass, or carotid artery bypass grafting were excluded specifically to make the data more homogeneous, bringing the total number of cases for analysis to 709.

Information related to demographics, comorbidities, operative indications, and perioperative complications were recorded prospectively at the time of surgery, before hospital discharge, or at the first clinic follow-up. Preoperative angiography was performed routinely.

Surgical technique included the use of general anesthesia exclusively. Stump pressures and MAPs were not always recorded for patients for whom an intraluminal

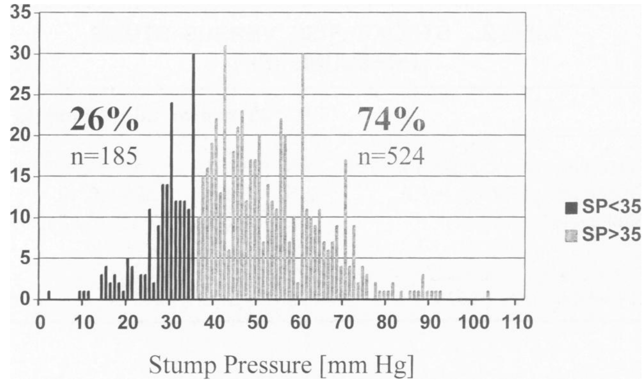

Figure 1. Histogram displaying frequencies of operative stump pressure measurements from 709 carotid endarterectomy procedures. Twenty-six percent of patients had a stump pressure less than or equal to 35 mmHg (n = 185), and 74% had stump pressure greater than 35 mmHg (n = 524). SP = stump pressure.

indwelling shunt was planned. Previous stroke, contralateral carotid artery occlusion, and SP less than 35 mmHg were general indications for shunt use. Electroencephalographic monitoring was routinely performed for the most recent 549 patients. The EEG was monitored continuously during surgery with a 16-channel machine (CNS Company, Eaton, OH) that allows observation of raw EEG output and its collection into color bar graphs for chronologic display. Technicians were present and they made subjective determination of an EEG change based on a decrease in amplitude (power) or decrease in delta wave activity. A neurologist was not present. Intraoperative electroencephalographic abnormalities were used as an adjuvant to SP measurements as an indication for intraluminal shunt use. Carotid arteriotomy patch angioplasty was employed for smaller ca-

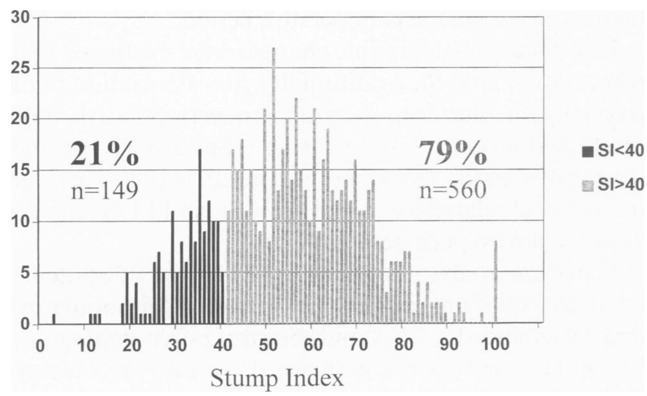

Figure 2. Histogram displaying frequencies of stump index, which was calculated retrospectively for 709 carotid endarterectomy procedures. Twenty-one percent of patients had a stump index less than or equal to 40 (n = 149), and 79% had a stump index greater than 40 (n = 560). SI = stump index.

Table 2. STROKE RISK VERSUS STUMP PRESSURE (SP)

	SP ≤ 35 mmHg	SP > 35 mmHg
Percentage of population (n = 709)	26% (185/709)	74% (524/709)
Percentage of CVA (n = 19)	68% (13/19)	32% (6/19)
Stroke rate *	7% (13/185)	1.1% (6/524)

CVA = cerebrovascular accident.
* Fisher's exact p = 0.0001.

rotid artery diameter. Stump pressure (as a mean pressure) and MAP (in the unclamped common carotid artery) were measured before arteriotomy with a 21-gauge needle connected to a pressure transducer. The SP and MAP were recorded prospectively, whereas SI was calculated retrospectively. Stump index was not used as a criterion for temporary intraluminal shunt placement in this series of patients.

Contralateral anatomy based on angiography data was used in conjunction with the SP to illustrate any existing correlation. The anatomic degree of stenosis was based on preoperative angiographic findings as measured (using the principles of the North American Symptomatic Carotid Endarterectomy Trial) and recorded by the surgeon at the time of operation. Carotid stenosis determined by duplex scanning methods was not included.

Endpoints for perioperative complications included 30 day postoperative cerebrovascular accident (CVA) and death. A CVA was considered to include any neurologic deficit that did not resolve completely within 24 hours of onset of symptoms. Among those patients suffering a stroke, subclassification of ipsilateral, bilateral, or contralateral to the side of operation were used. Furthermore, a differentiation between hemorrhagic *versus* ischemic stroke was made. Cause of death was recorded for all patients who died in the perioperative period.

Electroencephalographic changes were evaluated with respect to SP and SI. Additionally, any association of intraoperative monitoring criteria to perioperative morbidity and mortality was evaluated. Sensitivity, specificity, positive predictive value, and negative predictive values were calculated for low SP, low SI, and EEG changes associated with perioperative CVA.

Statistical analysis was performed by use of Student's t test to assess any differences between the population that experienced a CVA and the stroke-free population. Chi-square analysis was performed to stratify risk factors and to identify subgroups, based on SI, SP, and EEG changes that correlate with perioperative CVA. Logistic regression with multivariate analysis was performed to characterize the variables that had the most influence on the SP and perioperative stroke rate.

RESULTS

Table 1 presents data related to patient characteristics for all 709 operative procedures, including demographics related to the side of operation, gender, and common comorbidities. The average age of the population was 67.3 ± 8.6 years. The majority (60.2%) of the operations were for male patients; the side of the operative procedure was split evenly between the left and right sides. Comorbidities for hypertension, diabetes mellitus, and smoking were common.

In the evaluation of the 709 operative cases for SP measurements, a normal gaussian distribution can be seen, with peak incidence at the population mean of 46.7 mmHg (Fig. 1). Similarly, the distribution of SI is centered around its mean value of 54.9, with what appears to be a more gaussian distribution curve (Fig. 2). When evaluating the 19 cases in which a perioperative stroke occurred, there was a disproportionately high number of strokes in the population of patients with low SPs (Table 2). The stroke rate for patients based on the measured operative SPs demonstrated a significant difference between those with SP ≤ 35 mmHg compared with those with an SP greater than 35 mmHg ($p < 0.0001$, Fisher's exact test) with stroke rates of 7.0% and 1.1%, respectively. This trend toward increased perioperative stroke risk for lower SPs is demonstrated in Figure 3, with perioperative stroke rates expressed as a function of SP.

Population characteristics are provided in Table 3, comparing the 19 cases with a perioperative stroke and the 690 stroke-free procedures. The mean SP for the 19 patients who experienced a stroke in the perioperative period was significantly lower than that for the stroke-free 690 cases at 31.9 ± 13.2 and 47.1 ± 15.2 mmHg, respectively ($p < 0.0001$, Student's t test). The mean SI for the two groups also was significant by Student's t test ($p < 0.0001$), with

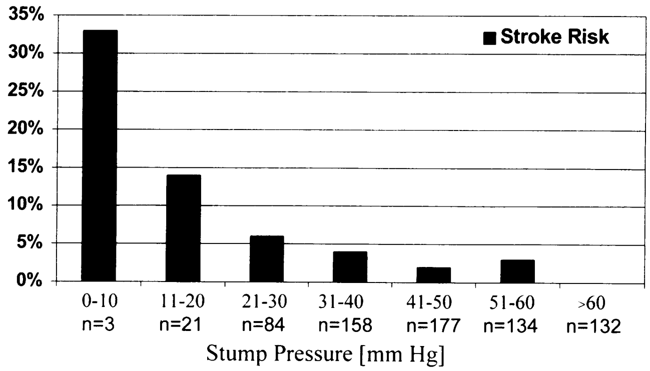

Figure 3. Observed perioperative stroke rate measured as a function of operative stump pressure (mmHg). There were 19 observed cerebrovascular accidents, with the highest stroke rates seen in patients with low stump pressure. There were no strokes in the 132 cases with stump pressure greater than 60 mmHg.

Table 3. PERIOPERATIVE STROKE *VERSUS* STROKE-FREE PROCEDURES

	Mean SP (mmHg)	Mean SI	Hypertension	Diabetes Mellitus	Smokers
No perioperative CVA (n = 690)	47.1 ± 15.2	54.7 ± 16.5	353/617 (57%)	112/672 (17%)	515/662 (78%)
Perioperative CVA (n = 19)	31.9 ± 13.2	38.8 ± 18.2	16/19 (84%)	5/19 (26%)	15/19 (79%)
p value*	<0.0001	<0.0001	<0.05	NS	NS

SP = stump pressure; SI = stump index; CVA = cerebrovascular accident; NS = not significant.
* Mean SP and SI compared by t test. Difference hypertension, diabetes mellitus, and smokers expressed as Fisher's exact p value.

values of 38.8 ± 18.2 and 54.7 ± 16.5. Hypertension was found to be an independent risk factor for perioperative strokes ($p < 0.05$) by chi-square analysis.

Perioperative strokes and deaths are presented in Table 4. The overall stroke rate for the series of 709 procedures is 2.7% (19/709). There were 18 ipsilateral CVAs, 2 of which were hemorrhagic strokes and 16 of which were ischemic. Both the hemorrhagic strokes were in patients who underwent surgery for high-grade stenosis and contralateral occlusion. One patient was found to have had a neurologic deficit corresponding to a CVA contralateral to the operative side on awakening from the anesthesia. One patient had a bilateral stroke and subsequently died on the third postoperative day. Perioperative mortality or mortality directly related to the operation was seen in 2 patients (0.3%) of the 709 in this series. Ten patients suffered an acute myocardial infarction perioperatively (1.4%); one of these patients subsequently died of cardiac failure (Table 4).

Table 5 illustrates the operative data with regard to the use of shunts, patches, SP, SI, and EEG data in relation to the perioperative stroke rate. There was an increased risk of stroke for patients in whom an intraluminal shunt was used, 4.6% compared with 1.6% ($p < 0.05$, chi-square analysis). There was no increased morbidity for patients who received patch angioplasty *versus* those closed in a primary fashion. With SP ≤ 35 mmHg as criteria for increased operative risk, the stroke rate in the perioperative period was 7.0%; compared with 1.1% for SP greater than 35 ($p < 0.0001$, chi-square analysis). Similarly, using SI ≤ 40 *versus* SI greater than 40, the stroke rates were 8.8% and 1.1%, respectively ($p < 0.0001$, chi-square analysis). Electroencephalographic monitoring was performed in the most recent 549 cases in which 12 perioperative strokes were documented, for a stroke rate of 2.2%. A change in the EEG occurred in 134 cases (24%). A perioperative CVA was documented in six patients for whom an EEG change was observed, for a stroke rate of 4.5% (6/134), compared with 6 CVAs in 414 patients without an EEG change, for a stroke rate of 1.4% ($p < 0.05$, chi-square analysis).

The sensitivity, specificity, positive predictive value, and negative predictive value for SP ≤ 35 mmHg, SI ≤ 40, and EEG changes are shown in Table 6. The highest sensitivity associated with perioperative CVAs was equal

Table 4. OPERATIVE COMPLICATIONS (N = 709 CEA)

Complication	Rate [no. (%)]	Perioperative Death [no. (%)]
All strokes (n = 709)	19 (2.7)	1 (0.14)
Ipsilateral ischemic CVA	15 (2.1)	0
Ipsilateral hemorrhagic CVA	2 (0.28)	0
Contralateral CVA	1 (0.14)	0
Bilateral CVA	1 (0.14)	1 (0.14)
Myocardial infarction	10 (1.4)	1 (0.14)

CEA = carotid endarterectomy; CVA = cerebrovascular accident.

Table 5. OPERATIVE DATA

	Perioperative Stroke Rate
Temporary intraluminal shunt*	
Shunt	12/259 (4.6%)
No shunt	7/450 (1.6%)
Patient was patched	5/184 (2.7%)
PTFE patch	4/162 (2.5%)
Saphenous vein patch	1/22 (4.5%)
Stump pressure†	
SP ≤ 35 mmHg	13/185 (7.0%)
SP > 35 mmHg	6/524 (1.1%)
Stump index	
SI ≤ 40	13/147 (8.8%)
SI > 40	6/562 (1.1%)
EEG monitoring*,‡	12/549 (2.2%)
No abnormalities throughout	6/415 (1.4%)
Changes at the time of carotid cross clamp	6/134 (4.5%)

PTFE = polytetrafluoroethylene; SP = stump pressure; SI = stump index; EEG = electroencephalogram.
p values were determined by chi square analysis: *$p < 0.05$ and †$p < 0.0001$.
‡ Continuous EEG monitoring complete for most recent 549 cases.

Table 6. INTRAOPERATIVE MONITORING CRITERIA ASSOCIATED WITH PERIOPERATIVE STROKES

Risk Criteria	Sensitivity*	Specificity†	PPV‡ (stroke rate)	NPV§	Shunt‖
SP ≤ 35 mmHg	68% (13/19)	75% (518/690)	7.0% (13/185)	98.9% (518/524)	89% (160/180)
SI ≤ 40	68% (13/19)	81% (556/690)	8.8% (13/147)	98.9% (556/562)	96% (134/139)
EEG change	50% (6/12)	76% (409/537)	4.5% (6/134)	98.6% (409/415)	77% (99/129)

SP = stump pressure; SI = stump index; EEG = electroencephalogram; PPV = positive predictive value; NPV = negative predictive value.
* Sensitivity refers to the percent of patients with a perioperative stroke meeting the risk criteria.
† Specificity refers to the percent of patients without a perioperative stroke who also did not qualify for the risk criteria.
‡ Positive predictive value gives stroke rate for the cohort of patients meeting that risk criteria.
§ Negative predictive value indicates the stroke-free rate for patients not meeting the risk criteria.
‖ Shunt indicates the percentage of patients in a given risk group who received a shunt during the procedure.

for SP ≤ 35 or SI ≤ 40, with 13 of the 19 (68%) events occurring in these patients by either criteria. The sensitivity for EEG changes was 50%. Stump index ≤ 40 demonstrated the most specificity at 81%, compared with 76% for EEG and 75% for SP. Also shown is the rate for which the intraluminal shunt was used as part of the operative technique.

The concomitant use of SP measurements and intraoperative EEG monitoring for patients is compared in Table 7. Patients with an SP ≤ 35 mmHg demonstrated an EEG change at the time of carotid cross-clamp in 66 of the 128 cases (52%). The results were similar for SI ≤ 40, with 62 of the 105 cases with EEG changes (59%). Both SP ≤ 35 and SI ≤ 40 were highly correlated to a change in the EEG ($p < 0.0001$, chi-square analysis). Conversely, higher SP and SI were associated with EEG abnormalities in only 16% of the cases.

Comparison of the anatomy of the contralateral internal carotid artery to the SI illustrates an inverse relationship, with a slight increase for contralateral stenosis of 75% (Table 8 and Fig. 4). Multiple regression analysis for SP and SI with age, gender, diabetes, smoking, hypertension, and contralateral stenosis for independent variables verified the significant difference in SP based on hypertension and contralateral anatomy ($p < 0.01$). Angiographic data for ipsilateral stenosis were available for 557 cases, whereas data for contralateral stenosis were recorded in 515 cases. As the contralateral stenosis increases up to 50% stenosis, the SI decreases slightly. However, the SI and pressure both increase slightly at 75% stenosis *versus* 50% stenosis. As the contralateral stenosis increases beyond 75%, the SI declines at a relatively faster rate. A comparison of the contralateral stenosis at SI ≤ 40 and SI greater than 40 was performed based on a weighted average for the contralateral stenosis, which was compared by Student's t test. For SI ≤ 40, the mean contralateral stenosis is 55.1%, whereas for SI greater than 40, the mean contralateral stenosis is only 35.1% ($p < 0.05$). The stroke rate was not significantly different based on the contralateral stenosis.

Table 7. CORRELATION OF STUMP PRESSURE (SP) AND STUMP INDEX (SI) TO EEG CHANGES

SP or SI	EEG Change [% (no.)]	No EEG Change [% (no.)]
SP ≤ 35 mmHg	52 (66/128)	48 (62/128)
SP > 35 mmHg	16 (68/421)	84 (353/421)
SI ≤ 40	59 (62/105)	41 (43/105)
SI > 40	16 (72/444)	84 (372/444)

SP = stump pressure; SI = stump index; EEG = electroencephalogram.

Patients with SI ≤ 40 and low MAP formed a high-risk subpopulation that was found to have an increased operative risk (Table 9). The stroke rate for these patients was found to be 30% (3/10) compared with 7.3% (10/137) in the patients with an SI ≤ 40 and MAP greater than 70 mmHg ($p < 0.05$, Fisher's exact test).

DISCUSSION

Carotid SP reflects the pressure transmitted through cerebral collateral arteries from the opposite carotid and the vertebral system. Therefore, it is not surprising that contralateral carotid anatomy predicts ipsilateral SP. That carotid SP would predict the perioperative stroke rate is less intuitive, particularly with the use of selective shunting. The relative merits of SP and EEG monitoring can be compared.

Stump Pressure and Contralateral Carotid Anatomy

In this study, SP and contralateral internal carotid artery anatomy were evaluated to determine their interde-

Table 8. ANATOMY RELATED TO CAROTID ENDARTERECTOMY AND STUMP INDEX

	All Patients (n = 709)	Perioperative CVA	Mean SP (mmHg)	Mean SI
Ipsilateral stenosis	n = 557	n = 18		
≤75%	112 (20%)	4 (3.6%)	47.4 ± 15.0	53.6 ± 16.8
76–89%	167 (30%)	4 (2.4%)	45.0 ± 14.4	52.8 ± 17.0
≥90%	278 (50%)	10 (3.6%)	46.0 ± 15.1	53.1 ± 15.9
Contralateral stenosis	n = 513	n = 13		
<25%	167 (32%)	6 (3.5%)	49.7 ± 15.3	58.5 ± 16.6
25%	114 (22%)	2 (2.6%)	46.2 ± 13.0	54.3 ± 15.6
50%	85 (17%)	3 (4.7%)	46.3 ± 16.7	53.2 ± 16.8
75%	45 (9%)	1 (2.2%)	47.7 ± 18.1	53.7 ± 15.4
90%	36 (7%)	0 (0%)	43.2 ± 13.7	49.4 ± 15.5
100%	66 (13%)	3 (4.5%)	36.6 ± 13.5	40.9 ± 13.3

CVA = cerebrovascular accident; SP = stump pressures; SI = stump index.

pendence. As more institutions move away from routine preoperative angiography in favor of noninvasive testing methods (magnetic resonance angiography, duplex, and spiral CT), gathering large samples of data with angiographically derived carotid artery anatomy will become more difficult. Although many previously reported studies have commented on the use of carotid SP measurements to direct operative decision management, a *quantitative* relationship with the contralateral carotid artery anatomy has never been fully elucidated.

An SI normalizes SP by dividing by the MAP. This removes variations in systemic blood pressure as a variable and produces values that correlate more accurately with the contralateral carotid and intracerebral anatomy. The general decline of both SP and SI with progressing contralateral stenosis is illustrated in Figure 4. This trend has been noted by Harada and others,[22] but the large numbers of patients in the current series allows

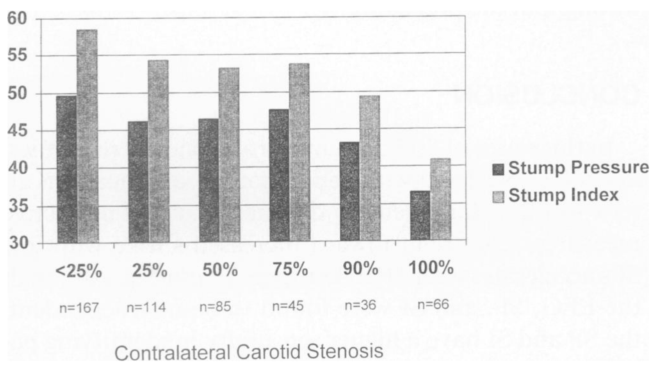

Figure 4. Correlation of measured stump pressure and stump index to angiographically determined contralateral carotid artery stenosis. Stump pressure and stump index show a generally inverse relationship to contralateral stenosis, with a slight increase for contralateral stenosis equal to 75%.

a quantitation over the entire range. The biphasic curve that is demonstrated for SI *versus* contralateral carotid stenosis shows an increase in the SI as the contralateral stenosis increases from 50% to 75%. For all other increases in the contralateral stenosis, the SI decreases. The slight increase did not achieve statistical significance, although it seemed to indicate a trend in the data. The most likely hypothesis to explain the increased pressure (or lack of a decrease) may be the development of cerebral collaterals over time. As the contralateral stenosis becomes critically severe (> 90%), the SI decreases precipitously, suggesting that flow through the collaterals is limited by inflow.

Risk Factors for Perioperative Morbidity and Mortality

By reviewing the operative SP measurements from 709 procedures, the increased incidence of operative complications despite shunt use in patients with lower SPs can be demonstrated. For SP values greater than 35 mmHg, the risk of perioperative stroke does not exhibit

Table 9. HIGH-RISK PATIENT POPULATION

	SI ≤ 40		SI > 40	
Operative Risk	MAP ≤ 70 (mmHg)	MAP > 70 (mmHg)	MAP ≤ 70 (mmHg)	MAP > 70 (mmHg)
Perioperative CVA	3/10 (30%)	10/137 (7.3%) p < 0.05*	1/78 (1.3%)	7/486 (1.4%)

MAP = mean arterial pressure; CVA = cerebrovascular accident.
* p < 0.05 for perioperative CVA based on chi square analysis.

a large amount of variability (Fig. 3). For the 132 patients with an SP greater than 60 mmHg, there were no strokes. For SPs less than 35 mmHg, the incidence of perioperative stroke demonstrates a steeply increasing risk. This increased incidence of perioperative morbidity is seen despite the use of temporary intraluminal indwelling shunts for virtually all of these patients. Therefore, patients with SP ≤ 35 represent a subset of patients who demonstrate a higher incidence of perioperative morbidity despite prophylactic cerebroprotective measures. Burke et al.[32] previously have noticed this significant difference in SPs ($p = 0.02$) with an average of 34.4 mmHg in patients with a neurologic event compared with 55.6 mmHg in those without. This pattern is not explained by the current study but is open to conjecture. Perhaps low SP reflects severe intracranial arterial disease in some patients, which results in stroke after cross-clamping despite shunting. Alternatively, low SP simply may correlate with generally severe carotid disease and mark those more likely to embolize during dissection or after endarterectomy.

Patients who received a temporary shunt demonstrated a higher rate of perioperative strokes compared with those who did not receive a shunt (4.6% *vs.* 1.6%; Table 5). Presumably a bias for the selective shunting of high-risk patients accounts for this difference. Unfortunately, there was no subset of patients randomized for the use of a shunt, and the distinction of shunt morbidity from selection bias cannot be determined from this study.

Patients with a history of hypertension also were found to have an increased risk of perioperative cerebrovascular events compared with normotensive patients. These patients also were seen to have a decreased SP compared with their normotensive counterparts. The correlation of hypertension to lower SPs may seem somewhat paradoxical at first, but the coexistence of additional risk factors probably contributes to more advanced intracranial atherosclerotic disease, which results in a lower SP and increased operative risk.

Although the patients with low SP and SI represent a higher surgical risk, further investigation of these cases identifies a select group with particularly high morbidity. In evaluating all cases with SI ≤ 40, the operative risk was compared based on the MAP as measured in the operating room. The patients with both a low SI and low MAP were seen to have significantly higher complication rate(30% *vs.* 7.3%). This trend may be reversed if the patient's operative blood pressure could be maintained at a higher level throughout the time of carotid cross-clamp. This finding prompts the recommendation, despite the small numbers involved, to artificially elevate the patient's mean arterial blood pressure to greater than 70 mmHg if their measured SP is low.

Stump Pressure and Electroencephalogram Monitoring

The use of routine EEG monitoring in addition to SP measurements did not begin until 1987. Consequently, the most recent 549 carotid endarterectomies in this series had both forms of monitoring routinely in use. Because the interpretation of the EEG is operator dependent, the data have been reported as either normal throughout the procedure (no change in EEG) or as an EEG abnormality reported verbally by the EEG technician during the operation. In reality, the actual waveform morphology and the location of the EEG abnormality are important factors for consideration. Additionally, the timing of the EEG change with respect to the operative course of events is very helpful. For example, an immediate change in the EEG after test clamping of the common carotid artery would be likely to reverse with the insertion of a shunt.

A change in the EEG does not necessarily indicate that infarction is imminent. In fact, EEG abnormalities were seen in 134 of the 549 procedures (24%). Most of the EEG changes were seen after clamping of the common carotid artery and were seen to reverse with the proper placement of a shunt. A smaller percentage of the EEG changes occurred after a considerable amount of time had elapsed from the clamping of the common carotid artery. In these cases, the use of the shunt was left to the discretion of the surgeon because it often was possible to rapidly complete the procedure and restore blood flow. If the EEG change occurred in a patient who already had an indwelling shunt for another reason (prior CVA, contralateral occlusion, or low SP), the shunt was checked for kinking and the procedure was completed in a timely manner. Only 6 of the 12 strokes (50%) occurred in patients with a documented EEG abnormality, indicating that 6 perioperative strokes were observed in patients who were not noted to have had any EEG abnormality throughout the procedure.

CONCLUSION

In this series of 709 primary carotid endarterectomies, low SP is correlated with perioperative complications after carotid endarterectomy despite the use of protective measures. The trend toward increased stroke with low SPs accelerates with SP to less than 35 mmHg. Although the EEG, SP, and SI were found to be interdependent, the SP and SI have a higher sensitivity in identifying patients at risk for postoperative complications. Electroencephalogram compliments SP as an intraoperative monitor and may decrease morbidity by a very small amount. When this modality is unavailable, excellent results may be expected using previous CVA, contralateral occlusion, or SP less than 35 mmHg as indications for shunt placement. The degree of stenosis of the contralateral internal carotid artery is related inversely to the SP. There is a slight increase in SP as the contralateral internal carotid artery stenosis increases from 50% to 75%, followed by a decline from 75% to 100%.

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Discussion

DR. NORMAN R. HERTZER (Cleveland, Ohio): Anyone who is familiar with the literature regarding carotid endarterectomy recognizes that there must be almost as many ways to do this operation well as there are to do it poorly. Good results have been reported—and bad results undoubtedly have gone unreported—for every possible mix of general *versus* local anesthesia, shunting *versus* nonshunting, and patch *versus* primary closure.

The basic message in the work just presented from Northwestern is that severe contralateral carotid disease tends to reduce the internal carotid stump pressure on the operated side, which in turn appears to correlate with a higher operative stroke rate. Intuitively, these data suggest that shunting probably should be considered in patients who have more than 75% stenosis of the opposite internal carotid artery even in the absence of other relative indications for its use.

The only potential problems with this conclusion are that the