Advances in the Surgical Treatment of Patients with Extracranial Cerebral Vascular Disease* **

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Introduction. Since the subject of surgery for carotid artery occlusive disease is too broad to be covered in its entirety, we will dwell primarily on some results of cerebral blood flow measurements and electroencephalograms performed during this procedure, their meaning and relationship to states of cerebral ischemia, and some controversial aspects of the surgery. An understanding of cerebral hemodynamics and the tolerance of neural tissue to ischemia is of major importance to any surgeon or physician dealing with this illness.

Cerebral Blood Flow Measurements during Carotid Endarterectomy. Cerebral blood flow (CBF) measurements, determined from intra-arterially injected ^{133}Xe have been performed routinely on all patients on the author's service undergoing carotid endarterectomy over the past four years, and therefore, flow data are available from 279 cases of carotid stenosis and 13 cases of carotid occlusion. These measurements have been determined prior to carotid occlusion, during occlusion, with a shunt in place (when used), and following restoration of flow. Analyses of results of these measurements have indicated an increase in CBF, determined by the initial slope technique from 58–73 ml/100 gm/min when carotid artery stenosis exceeds 90% (1). When carotid artery stenosis is less than 90%, analysis of these measurements has indicated no essential change in CBF. These measurements have been recorded with the patient under general halothane anesthesia with moderate induced hypertension and with a constant Pa_{CO_2} of 42 torr. Therefore, these anesthetic CBF measurements are higher than those found in normal awake patients, where a normal CBF approximates 54 ml/100 gm/min. I do not wish to imply that an increase of CBF in this setting, of this magnitude, is necessarily lasting or of clinical significance other than an area's susceptibility to symptomatic emboli.

It is necessary to distinguish between the change in absolute regional CBF and alteration in relative contribution to that flow from the internal carotid artery before and after endarterectomy. Even in instances where no true alteration in CBF could be determined by these types of measurements, Boysen (2) found an increase in internal carotid artery flow following endarterectomy, and therefore an increase in the relative contribution to CBF from the vessel operated upon, when a significant stenosis was present.

Electroencephalographic Measurements during Carotid Surgery. In addition to CBF measurements, all patients undergoing endarterectomy now have a constant electroencephalogram (EEG) recorded from the time of induction-of-to-arousal-from anesthesia. It has been found that the EEG is a valuable monitor for evaluating cerebral function during this surgery with a properly maintained level of anesthesia (3). It is noninvasive, has no risk, and has proven to be highly accurate in correlating cerebral metabolic function during surgery with the neurological function postoperatively. The EEG offers a continuous technique for monitoring cerebral function throughout the entire procedure, something that is not possible by any other technique unless

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the patient is operated upon under local anesthesia. The very close correlation between the EEG and the CBF measurements below 17–18 ml/100 gm/min at a Pa_{CO_2} of 40 torr is most impressive. In our series to date, we have not had a single CBF measurement during carotid occlusion below this level that did not have an associated EEG abnormality. The lower the occlusion flow, the more rapid the EEG changes. A typical EEG demonstrating the changes with occlusion and resolution with a shunt in place is illustrated in Figure 1.

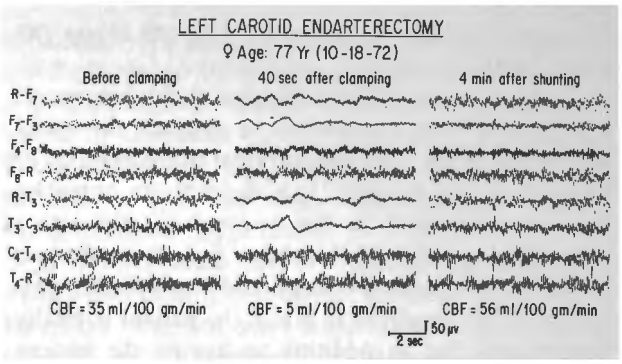

Fig. 1—A typical EEG demonstrating the changes seen with occlusion for endarterectomy when cerebral blood flow falls to 10 ml/100 gm/min. Changes include both generalized slowing and loss of background activity. In this patient with opposite carotid artery occlusion, the changes were seen bilaterally. Most commonly, changes occur only on the side of occlusion. The EEG improves following placement of the shunt and improvement in CBF values doubles that seen prior to occlusion. (Reprinted by permission from *J Neurosurg* 41:315, 1974.)

CBF-Ischemic Tolerance Ratio. The ischemic tolerance of neural tissue is directly proportional to the relative decrease in CBF. A decrease in CBF to between 20 and 30 ml/100 gm/min can be tolerated quite well for limited periods of time. When the CBF falls to below 18 ml/100 gm/min, cerebral metabolic function changes and a physiological paralysis follows (1, 3). This is, however, to be distinguished from infarction. It is probable that this degree of ischemia can be tolerated for a period of hours, rather than minutes, without major infarction, whereas flow reductions below 10 ml/100 gm/min produce infarction in a much shorter time.

This hypothesis cannot be tested in its entirety clinically, but it has been extensively investigated in the laboratory. In squirrel monkeys, a degree of ischemia approximating 20 ml/100 gm/min can be tolerated for up to two hours without the uniform development of a cerebral infarction (4). In these animals cerebral adenosine triphosphate (ATP) falls to 55% of normal and cerebral lactate rises to seven times normal following two hours of occlusion (5). During the period of occlusion, the EEG shows changes similar to those seen in patients with severe flow reductions during carotid occlusion. Following restoration of flow in the laboratory preparation, there is a gradual rise in ATP, fall in lactate, and normalization of the EEG. An infarction is not uniformly seen in this animal unless occlusion is maintained for four hours. The degree of ischemia and metabolic alteration which follows this single major vessel occlusion must be distinguished from the situation which follows cardiac arrest when there is zero blood flow. In this setting, ATP falls to 25% of normal in only four minutes, and there is the rapid production of cerebral infarction with the probability of the "no-reflow phenomenon" (6).

We had previously doubted the necessity for a shunt in any case undergoing carotid endarterectomy, on the basis that flow values seldom if ever fell to extremely low levels (7). It is now apparent that this hypothesis was incorrect and that, indeed, a great many patients have CBF measurements with unilateral carotid artery occlusion that fall to appallingly low levels, and in some instances, to values too low to measure, approximating cardiac arrest. Furthermore, unfortunately, we have found that the degree of backflow is proportional to the cerebral vascular resistance which varies quite a bit from one patient to another; that is, it is an unreliable indicator of CBF and collateral flow. In contrast to our previous position, we now readily agree that there are definite indications for a shunt during carotid endarterectomy.

Use of a Shunt during Carotid Endarterectomy. A shunt has been employed in approximately one-third of the patients operated upon in this series. EEG changes, along with occlusion values below the critical perfusion level, occurred in 56 of these patients; shunts were used in the remaining cases because of borderline perfusion values that could conceivably produce a critical perfusion flow in the internal capsule area, which might be missed both by a CBF measurement and an EEG change.

Shunts are not used routinely because there are several disadvantages in using them. A shunt interferes with a precise endarterectomy, can serve as a source of emboli when in place, and requires constriction of the proximal carotid artery in a

tourniquet fashion, a maneuver that can injure the vessel wall.

The time for placement of a shunt has varied a great deal from one patient to another; the speed of placement has been proportional to the urgency of its need. When possible, it is desirable to complete the endarterectomy in the internal carotid artery prior to placement of the shunt and, thereafter, to complete the endarterectomy and angioplastic procedure. With the shunt in place, the patient is totally heparinized, but in addition to having the patient totally heparinized, the shunts we are using are impregnated with heparin to avoid or minimize the possibility of emboli. Using this new type of heparin coating, provided for us by Battelle Laboratories of Columbus, Ohio, we have seen no platelet material at the mouth of the shunt following its removal. Prior to this added measure, even with total heparinization of the patient, we routinely found platelet material at the mouth of the shunt.

To this date, none of our patients has developed an abnormal EEG with carotid occlusion that did not revert with prompt placement of a shunt; however, one patient in the group did develop EEG alterations with the shunt in place, proven to be related to microembolism through the shunt, and this patient sustained a permanent neurological deficit. Since that occasion, we have been using only heparinized shunts and have had no recurrent problems of that nature. This patient represented the only embolic complication from the group in which a shunt was employed.

CBF, Ischemic Tolerance, and Pa_{CO_2}. We have not routinely employed hypercapnia during the period of carotid occlusion. Under halothane general anesthesia, hypercapnia predisposes to cardiac arrhythmias, giving problems not justified by proven beneficial effect. Boysen (2) found, during carotid endarterectomy, the expected increase in CBF prior to carotid clamping from hypercapnia as a result of maximal vasodilatation. With carotid clamping, however, there was a greater relative reduction in CBF in comparison to the group studied at normocapnia, and furthermore, a paradoxical reaction was occasionally demonstrated. In this paradoxical reaction, hypercapnia did not improve regional CBF but rather resulted in an intracerebral "steal." We have demonstrated this in our patients also and it therefore seems safe to conclude that hypercapnia cannot be relied upon invariably to increase regional perfusion in the areas of severe ischemia.

The use of hypocapnia, to produce a reverse steal and hence increase cerebral perfusion to areas of ischemia, has been suggested by Lassen (8); however, a careful analysis of their patient group with proven cerebral ischemia, treated with hypocapnia, indicated no clinical effect from hypocapnia, although they were able to produce a reverse steal with its use.

Laboratory studies support the clinical findings of Lassen and his group (9) and have indicated that although a reverse steal can be produced with the use of hypocapnia, the effect of hypocapnia in areas of focal ischemia is definitely detrimental. In a group of animals with focal ischemia in which hypocapnia was induced, the cerebral ATP was significantly less and the cerebral lactate significantly higher than corresponding values in hypercapnic and spontaneously breathing animals. One must conclude that the Pa_{CO_2} should be maintained at as near a normal level as possible during carotid endarterectomy and that it should not be raised to produce hypercapnia or lowered to produce hypocapnia.

Surgical and Nonsurgical Lesions. I should now like to refer to some of the clinical and surgical aspects of this illness. The majority of patients upon whom we operated in this series have had a severe stenosis or a deep ulceration at the origin of the internal carotid artery from the common carotid artery. Minor degrees of ulceration at the origin of the internal carotid artery from the common carotid artery are not considered surgical lesions unless the patient is quite young. It has been our judgment that such small ulcers frequently heal spontaneously, and this is supported by a recent study designed to determine the frequency of strokes from such lesions. Minor degrees of ulceration or stenosis at the origin of the internal carotid artery are not uncommon in the elderly population, and even when associated with a bruit, are not necessarily an indication for surgery. Loops of the internal carotid artery are rarely symptomatic—notwithstanding a recent report to the contrary.

Correlation of Angiographic Findings with Symptom Complexes of Carotid Arterial Disease. A correlation, retrospectively, of the angiographic findings, cerebral blood flow measurements, and clinical symptomatology in patients suffering from carotid ulcerative stenosis has permitted a judgment regarding the etiology of the various forms of symptomatology. In general, the focal symptom complexes are felt to be most commonly the result of

cerebral embolization (10), but we have noted that focal regions of the brain, and to a lesser extent the retina, are particularly vulnerable to emboli if that region is under a low perfusion pressure; this is an angiographic finding—space does not permit us to discuss it in detail. In such instances, regions of marginal perfusion are dependent in part on collateral circulation, so that any embolus to a collateral vessel is likely to be of major significance symptomatically. Obviously, such regions of marginal perfusion are also particularly vulnerable to periods of hypotension. In general, amaurosis fugax, transient ischemic attacks (TIA's), and small completed infarcts represent manifestations of cerebral embolization (11). A progressing stroke—that is, a neurological deficit which is progressive over a period of hours—quite often is the result of multiple embolization into a region of very marginal perfusion. The temporal profile of this type of progressing stroke must be distinguished from a massive infarction that reaches its zenith two or three days later from severe cerebral edema. The progressing stroke which begins with a minor neurological deficit and progresses through intermittent stages of deterioration can be helped by emergency surgery in many instances, whereas the massive infarction with immediate profound hemiplegia is often a contraindication to surgery.

Generalized cerebral ischemia represents an uncommon, nonembolic, symptom complex that may be the patient's only complaint or may coexist with symptomatology of focal cerebral ischemia (12). An individual with generalized cerebral ischemia must be differentiated from the patient with vertebrobasilar insufficiency; these patients are suffering from severe bilateral carotid arterial stenosis or a high-grade stenosis in association with a contralateral occlusion. Upon assuming the erect posture, there is a rather dramatic fall in the retinal artery pressures, although the peripheral blood pressure does not fall proportionately. At this time, the patient may complain of light-headedness or a sensation that he may faint. This is not true vertigo. He may complain of dimness of vision or difficulty in balance. The family usually reports changes in behavior or memory. CBF measurements have indicated a very significant increase in CBF following endarterectomy in these patients, and there has been a rather gratifying improvement following surgery. Approximately 10% of our patients have had symptomatology of this type. I would like to reemphasize that these are not patients with presenile dementia or vague lightheadedness. In addition to the symptoms, there are the hard findings of reduced retinal artery pressures, bilateral or unilateral carotid bruits of a very significant character, and subsequent angiographic confirmation of the pathology—severe disease—not kinking or minor irregularities.

It is uncommon that we operate on patients for the presence of a bruit alone; however, the character of the bruit and other features of the examination, such as the presence or absence of retinal emboli, the patient's age, and the presence or absence of vascular disease elsewhere, enter into the decision regarding the method of treatment.

Preoperative Risk Factors in Carotid Endarterectomy. Space does not permit details of our system for grading a patient's risk for surgery and the morbidity and mortality related to these risk factors, which include obesity, advanced age, coronary artery disease, progressing neurological deficits, frequent daily transient ischemic attacks, contralateral arterial occlusion, high bifurcations, long plaques, and soft thrombi. This system is graded from I through IV for carotid stenosis, acute internal carotid occlusion being considered grade V and analyzed separately. The combined morbidity and mortality in this series has ranged from 1% in low-risk, or grade I, patients for surgery to 8% in high-risk grade IV patients for surgery (12).

Vessel Patency. Patency in all vessels on which we have operated for ulcerative stenotic disease was 99.3% at the time of discharge from the hospital as determined by retinal artery pressure (RAP) measurements, angiography, or both; however, four vessels were reopened prior to discharge with insertion of a vein graft because of occlusion in the immediate period following surgery. All of these occurred earlier in the group in which grafts were not employed; all were symptomatic with TIA's; all occurred in relatively small vessels; and all were detected or confirmed by finding a reduction in the RAP which in each case returned to normal after restoration of flow and patency. In the first patient, reopening was delayed and a permanent upper monoparesis and mild expressive aphasia resulted. In the other three patients, the vessels were immediately reopened, and there was no delay in discharge from the hospital and no morbidity. One vessel in a grade IV candidate occluded simultaneously with a myocardial infarction; flow was

not restored and hemiplegia resulted; this has been our only permanently occluded artery.

To Patch or Not To Patch. Admittedly one can perform this surgery without the use of a patch and have the vessel remain patent in most instances. There is little question in my mind at this time, however, that the use of a patch improves the prognosis for both acute and chronic patency. The use of a patch prolongs the procedure, but with careful monitoring, this is of no great importance. We frequently reinforce the portion of the graft in the common carotid artery with a thin teflon sheath to prevent an aneurysmal dilatation and excessive stress on the graft in patients who are hypertensive.

Hemorrhagic Infarction. The final controversial subject I would like to discuss is that related to the risk of hemorrhagic infarction. This risk has led some surgeons to consider the presence of any recent neurological deficit and certainly a progressing deficit as a relative contraindication to surgery (13). The controversy is not easily resolved. Our group of patients who were neurologically unstable at the time of surgery, considered as grade IV risks, embraces a group of 56 patients in whom we have had an 8% combined morbidity and mortality; the risks of not operating are obviously considerably higher. This group includes progressing strokes, frequent daily TIA's, impending occlusion with ischemic carotid pain, and recent minor fixed deficits in association with severe degrees of ulceration.

Hemorrhagic cerebral infarction can result from cerebral embolization with or without surgery (14). A very high risk of surgery in these unstable neurological patients is related to a soft thrombus that is frequently present at the bifurcation of the carotid artery and is superimposed upon an ulcerated plaque. In these patients, extra care must be exercised in preventing a recurrence of cerebral embolization. It would seem likely that hemorrhagic infarction has often resulted from embolization rather than restoration of perfusion pressure to an ischemic region of brain.

The combination of a reduced retinal artery pressure on the side of intended surgery, and a major branch occlusion intracranially with a region of severe ischemia represents, in our judgment, a contraindication to surgery.

Conclusion. The use of intraoperative CBF measurements, continuous EEG's, postoperative RAP's, vein patches, and intraoperative shunting when indicated, has aided materially in reducing morbidity and mortality in this surgery.

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