Regional cerebral blood flow studies following superficial temporal-middle cerebral artery anastomosis

M. Peter Heilbrun, M.D., O. Howard Reichman, M.D., Robert E. Anderson, M.D., and Theodore S. Roberts, M.D.

Division of Neurosurgery and Department of Radiology, University of Utah Medical Center, Salt Lake City, Utah, and Division of Neurosurgery, Loyola University Medical Center, Maywood, Illinois

Regional cerebral blood flow (rCBF) studies were performed during the postoperative period on 16 patients with internal carotid occlusions and inaccessible stenoses, and middle cerebral artery occlusion and stenoses, who underwent superficial temporal artery-middle cerebral artery (STA-MCA) anastomoses. The intra-arterial xenon method with selective application of the xenon bolus through the internal carotid and the newly established superficial temporal channel has allowed comparison of the flow provided by the pathological input with flow through the new input. The results show that initial rCBF (rCBF₁) was globally reduced in all patients to a mean of 28.4 ± 11.9 ml/100 gm/min at a mean pCO₂ of 29.6 ± 9.55 mm Hg. Patients with transient ischemic attacks (TIA) and minor strokes with minimal residua (RIND) had a mean rCBF₁ of 30.4 ± 11.6 ml/100 gm/min at a mean pCO₂ of 30 ± 10 mm Hg, while patients with completed strokes had a mean rCBF₁ of 25.0 ± 12.4 ml/100 gm/min at a mean pCO₂ of 29.1 ± 8.8 mm Hg. There was no significant difference between these two groups. This finding suggests that in this small group of patients with TIA's and RIND's, the cause of the stroke is probably related more to decreased perfusion than embolus, and may explain why these patients' symptoms improve after STA-MCA anastomosis. The results of this study suggest that in addition to an inaccessible lesion, global or focal decreased rCBF is a necessary criterion in the definition of indications for intracranial revascularization procedures.

KEY WORDS: regional cerebral blood flow • stroke • STA-MCA anastomosis • transient ischemic attacks

Anastomosis of the superficial temporal artery to the middle cerebral artery cortical branches (STA-MCA) is a useful procedure for providing additional channels of collateral circulation to the brain. It has been demonstrated that these new channels will remain patent and will also enlarge with time. This procedure has been used in the treatment of patients with cerebrovascular disease presenting as transient ischemic attacks (TIA), completed strokes followed by incomplete resolution which has been termed reversible ischemic neurological deficit (RIND), and completed
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strokes (CS), who have been shown to have extracranial internal carotid occlusions and siphon stenoses, and middle cerebral artery (MCA) occlusions and stenoses.

Cerebral blood flow studies have been performed to determine if this technique is of value in choosing which patients might benefit from the procedure, and also in assessing the value of the procedure in providing increased collateral circulation.\(^5\)\(^6\) Theoretically, the value of STA-MCA anastomoses relates to the question of whether the pathogenesis of TIA's and RIND's is secondary to decreased total brain perfusion from inadequate collateral in the presence of occluded or stenosed vessels, or secondary to emboli associated with ulcerated atheromatous plaques. Skinhøj, et al.\(^5\) favor the embolic theory, which is based on the demonstration that patients with typical TIA's irrespective of the associated vascular lesion, have no significant decrease in flow or loss of autoregulation, while patients with completed strokes have both focal and global flow abnormalities with loss of autoregulation and changes in CO\(_2\) reactivity. If it could be demonstrated that the small group of patients with TIA's and RIND's who have internal carotid occlusions and intracranial occlusions and stenoses show significant decreases in flow, then one might have evidence that the attacks are more often due to hemodynamic causes than emboli.

We have attempted to answer this question by measuring regional cerebral blood flow (rCBF) by the xenon clearance method in patients undergoing STA-MCA anastomoses during the postoperative period. Careful consideration of the technique of performing the rCBF studies was necessary to minimize extracerebral isotope contamination in the presence of the new collateral channel. For this reason, we elected to measure rCBF by selective application of the xenon bolus first through the internal carotid input, and second through the newly established superficial temporal channel. We concluded that since the internal carotid flow value represents the pathological input channel, comparison of those patients operated for TIA's and RIND's with those patients operated for completed stroke would indicate whether decreased perfusion was present. If decreased flow was present, then comparison of the flow through the pathological input to the flow through the newly established channel might indicate capability of the superficial temporal artery to provide additional collateral flow to the brain.

**Materials and Methods**

The xenon bolus injection method used in this study has been described previously\(^2\)\(^3\) ex-cept for the following modifications. Rather than percutaneous catheterization of the internal and external carotid arteries in the neck, all of the studies were performed through the transfemoral route. A small-diameter No. 6 polyethylene catheter was used to catheterize selectively the internal carotid and the external carotid arteries just below the take-off of the superficial temporal artery. Xenon in saline in doses of 1.5 to 3.5 mCi was injected. Counting rates and clearance curves were obtained with eight small scintillation probes grouped extracranially over the angiographic Sylvian triangle.\(^5\) Regional cerebral blood flow was calculated as the rCBF\(_i\) for each individual probe, and global flow as the mean rCBF\(_i\) of the eight channels.\(^4\) The initial slope method of calculating blood flow was based on the assumption that in normal patients the clearance curve for approximately the first 2 minutes is generally monoexponential and represents predominantly gray matter or fast flow. The rCBF\(_i\) is proportional to the slope of the logarithmically displayed clearance curve. Olesen, et al.\(^4\) have shown that the initial slope method correlates satisfactorily with other methods of calculating cerebral blood flow and is very practical when sequential studies with multiple detectors are used. Angiography was performed prior to the flow study with approximately a 15-minute period between each injection. All of the studies were performed at the University of Utah Medical Center, at an altitude of 5000 feet above sea level. Normal rCBF\(_i\) values for this altitude were calculated from five patients undergoing angiography for evaluation of possible neurological disease; the mean rCBF\(_i\) was 45.7 ± 13.8 ml/100 gm/min, and the mean pCO\(_2\) was 28.6 mm Hg.

**Results**

**Internal Carotid Artery Occlusion**

**Quantitative Analysis of rCBF\(_i\) Values.** In the group of six patients with internal carotid artery occlusion, three patients had TIA's
and RIND's, and three patients had completed strokes (Table 1). At the time of angiography, all patients had the anastomosis open, although there was one late closure due to occlusion of the common carotid artery at the aortic arch. The three patients with TIA's and RIND's had a mean rCBFI of 28.5 ml/100 gm/min at a pCO₂ of 32 mm Hg, while the patients with completed strokes had a mean rCBFI of 23.6 with a mean pCO₂ of 32 mm Hg.

Qualitative Analysis of rCBFI Clearance Curves. In normal patients, the first 2 minutes of the logarithmically displayed clearance curve is approximately monoexponential. It has been demonstrated in patients with damaged brains secondary to trauma that the first 2 minutes of the logarithmically displayed clearance curve is often not monoexponential, but multixponential. The multicompartamental clearance curve suggests that varied flow rates may be present within the damaged gray matter. In addition, in normal patients, intrachannel flow values are small and the grouped clearance curves appear homogeneous. In our normal patients, the intrachannel variation was 10.2%. However, in ischemic brain associated with...
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vascular disease, intrachannel flow values are often quite variable and groups of clearance curves appear heterogeneous.\(^8\)

In this group of patients, both monoexponential and multiexponential flow clearance curves were found. When single curves were monoexponential, generally the group of eight curves were homogeneous and were classified as Type 1. When the single curves were multiexponential, generally the group of eight curves was heterogeneous and classified as Type 2. There did not appear to be any correlation between the quantitative flow data and the type of clearance curves. However, when the type of clearance curve was compared to the pattern of collateral circulation seen on the angiographic study, there appeared to be some correlation. Type 1 consisted of generally monoexponential and homogeneous \(rCBF_1\) curves. These curves were seen when the flow was provided primarily by the input vessel being examined, either the internal carotid or the superficial temporal artery. In Type 1 patterns, natural collateral flow through the circle of Willis or leptomeningeal vessels was poor. Type 2 with multiexponential and homogeneous curves were seen when there was mixed perfusion between the input vessel being examined and naturally-occurring circle of Willis and leptomeningeal collateral flow.

Case 1 is an example of Type 1, and had complete postoperative resolution of TIA’s. The angiogram in that case showed complete filling of the middle cerebral vessels from the shunt through anastomosis of two branches of the superficial temporal artery (Fig. 1). There was minimal crossover of dye from the contralateral unobstructed internal carotid artery through the circle of Willis (Fig. 2). The actual logarithmically displayed 2-minute clearance curves from eight detectors grouped closely over the angiographic Sylvian triangle, from which the \(rCBF_1\) is calculated are shown in Fig. 2 lower left; the clearance curves were monoexponential and generally homogeneous.

Case 3, an example of Type 2, was postoperatively asymptomatic from RIND. The angiogram showed partial filling of the middle cerebral group through the anastomosis of one branch of the superficial temporal artery, but good filling through an already existing collateral (Fig. 3). In contrast to the first case, the flow curves were multiexponential and markedly heterogeneous.

Middle Cerebral Artery Occlusion

Quantitative Data. In the group of patients with middle cerebral artery occlusion, one patient had TIA’s and two had completed strokes (Table 1). At the time of angiography, all channels were open. In Case 9, symptoms recurred at 17 months, at which time the anastomosis, which initially was open, was shown to be closed. This was followed by an occipital artery-middle cerebral branch anastomosis, after which he had further resolution of symptoms. This patient, who had TIA’s, had an \(rCBF_1\) of 30.3 ml/100 gm/min at a \(pCO_2\) of 27 mm Hg, while the two patients with completed strokes had a
Fig. 2. Case 1. Upper Left: Injection of contrast material through unobstructed right internal carotid artery showing minimal crossover through the circle of Willis. Right: Anteroposterior view of middle cerebral vessels filled through the anastomosis. Lower Left: Diagram of Type 1 monoexponential homogeneous xenon clearance curves. Each circle represents the position of each of the eight probes. Within each circle is the logarithmically displayed 2-minute xenon clearance curve from which the rCBF is calculated. The mean rCBF of the eight probes = 37.5 ml/100 gm/min, at a pCO2 of 43 mm Hg.

mean rCBF of 26.8 ml/100 gm/min at a pCO2 of 28 mm Hg. The two patients with completed strokes had blood flow in the ischemic range.

Qualitative Analysis of the Clearance Curves. Case 8, an example of Type 1 flow clearance curves, had a mild completed stroke. Postoperatively, he had no change in his symptoms. His angiogram showed one-vessel anastomosis with excellent filling of the whole middle cerebral group (Fig. 4 upper). The flow curves were monoexponential, only mildly heterogeneous, with moderately decreased flow and similar flow values through the internal and external carotid channels (Fig. 4 lower). In the patients with completed strokes, the finding of similar but ischemic flow values in regions supplied by both the internal carotid input and the newly established superficial temporal input suggested that the flow might be determined mainly by the metabolic demand of the tissue. If the flow was determined by the increased capability of the new superficial temporal input to carry blood, then one would expect a higher flow through the new input, as compared to the pathological input.

Internal Carotid Siphon and Middle Cerebral Artery Stenosis

Quantitative Data. In the group of patients with internal carotid siphon and middle cerebral artery stenoses (Table 1), the six patients with TIA’s and RIND’s had a mean rCBF of 31.3 ml/100 gm/min at a pCO2 of
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**FIG. 3.** Case 3, with internal carotid occlusion. **Upper:** Angiograms with injection of contrast material through unobstructed left internal carotid artery reveals excellent crossover through the circle of Willis and leptomeningeal collaterals. **Lower Left:** Partial filling of middle cerebral vessels through anastomosis of a single branch of the superficial temporal artery. **Lower Right:** This patient showed Type 2 multiexponential heterogeneous xenon clearance curves. Mean rCBF, of the eight probes = 28.5 ml/100 gm/min, at a pCO₂ of 30 mm Hg.
Fig. 4. Case 8. Upper Left: Angiogram showing middle cerebral occlusion. Upper Right: Excellent filling of middle cerebral vessels through anastomosis (arrow). This patient showed Type 1 monoexponential homogeneous clearance curves with xenon injected into the internal carotid artery. Lower Left: Mean rCBF₁ = 30.0 ml/100 gm/min, at a pCO₂ of 30 mm Hg. Lower Right: Similar Type 2 clearance curves were obtained with xenon injected into the superficial temporal artery. Mean rCBF₁ = 26.3 ml/100 gm/min, at a pCO₂ of 29 mm Hg.

28.5 mm Hg, while the one patient with a completed stroke had a mean rCBF₁ of 25.8 ml/100 gm/min at a pCO₂ of 23 mm Hg. Postoperatively all of the TIA and RIND patients were asymptomatic and the patient with the completed stroke was improved. The angiogram showed that the anastomosis was open in all patients.

Qualitative Analysis of the Clearance Curve. In this group of patients, most of the angiographic flow was by way of the internal carotid artery, rather than the newly established anastomosis, even after two branches of the superficial temporal artery were utilized. Case 11, with two anastomotic branches, showed most of the filling through the anastomosis (Fig. 5 upper). The rCBF₁ flow was higher through the anastomosis than through the internal carotid artery. The internal carotid flow curves were monoexponential while three of the eight superficial temporal curves were multiexponential. This pattern suggests that the stenotic middle cerebral artery cannot carry enough blood, and that most of the flow is provided by the new superficial temporal artery and is aided by some leptomeningeal collateral flow. Case 10, an example of Type 2 flow clearance curves, also had an anastomosis with two branches; however, the postoperative angiogram showed most of the filling through the internal carotid artery rather than the shunt (Fig. 6). This is reflected in the flow curves, where most of the flow is provided by the middle cerebral artery, even though it is stenotic. There is little flow through the new superficial temporal artery, even though two branches were anastomosed.
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**Results in TIA and RIND Patients vs Completed Stroke Patients**

There was no significant difference in the mean rCBF, between the 10 patients with TIA’s and RIND’s and the six patients with completed strokes. Analysis of variance between the six rCBF, values (Table 2) showed no significant difference at the .95 level. A t-testing comparing the total TIA and RIND group to the completed stroke group showed no significant difference in rCBF, or pCO2 values. Moreover, all global rCBF, values were below 31 ml/100 gm/min, and were considered ischemic.

**Discussion**

While the group of patients with TIA’s studied by Skinhøj, et al., had generally normal global flow in comparison to a group of patients with completed strokes who had globally decreased flow, we have found globally decreased flow in our whole group of patients with no significant difference between patients with TIA’s and RIND’s and those with completed strokes. This finding suggests that the majority of patients with all forms of cerebrovascular symptoms, from internal carotid occlusions or occlusions or stenoses within the cranial vault, are more often due to hemodynamically decreased perfusion, rather than emboli. This, however, would not exclude the possibility of embolic phenomena being superimposed on areas of decreased perfusion. In fact, emboli to cortical branches have been observed in the form of occluded vessels angiographically by direct visualization at the time of surgery. Since the majority
FIG. 6. Case 10. Upper: Angiograms showing middle cerebral stenosis (arrow). Lower Left: Partial filling of middle cerebral vessels through anastomosis (arrow). Lower Right: Type 2 multiexponential heterogeneous clearance curves. With xenon injected into the internal carotid artery (above), mean rCBF was 33.5 ml/100 gm/min, with a pCO₂ of 27 mm Hg. With xenon injected into the superficial temporal artery (below), mean rCBF was 20.8 ml/100 gm/min, with a pCO₂ of 27 mm Hg. Note the higher mean rCBF with superficial temporal xenon injection compared to internal carotid injection.
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TABLE 2

Comparison of results in patients with TIA's and RIND's to those with completed stroke*

<table>
<thead>
<tr>
<th>Pathology</th>
<th>TIA &amp; RIND (n = 10)</th>
<th>Completed Stroke (n = 6)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>rCBFᵢ (ml/100 gm/min)</td>
<td>pCO₂ (mm Hg)</td>
</tr>
<tr>
<td>ICA occlusion</td>
<td>28.5 ± 18</td>
<td>34 ± 15.6</td>
</tr>
<tr>
<td>MCA occlusion</td>
<td>30.3</td>
<td>27</td>
</tr>
<tr>
<td>ICA &amp; MCA stenosis total</td>
<td>31.3 ± 9.9</td>
<td>28.5 ± 5.2</td>
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<td></td>
<td>30.4 ± 11.6</td>
<td>30 ± 10</td>
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* TIA = transient ischemic attack; RIND = reversible ischemic neurological deficit; ICA = internal carotid artery; MCA = middle cerebral artery.

of patients with TIA's and RIND's improved following surgery, this fact alone suggests that the neurological deficit was on the basis of low perfusion. There is no reason to believe that the presence of a new anastomotic channel should prevent emboli, although one might suppose that flow through the new channel might stop the emboli from propagating to distal cortical branches.

Do the flow values seen in this group of patients support the improvement in clinical status that was noted? As we have demonstrated, interpretation of the flow data is complex since it involves pathological input channels through the internal carotid system. Superimposed on this is the new collateral channel through the superficial temporal artery. Our studies would suggest that in patients with internal carotid artery occlusion, when the angiogram shows excellent filling and the flow curves are monoexponential, the majority of the flow comes through the shunt. When the angiogram, however, showed that most of the filling is through the circle of Willis or leptomeningeal collaterals, rather than the shunt, the flow patterns (Type 2) were generally multiexponential and heterogeneous. Although one assumes that the xenon bolus, delivered through either the internal carotid or the new superficial input, arrives instantaneously, the finding of multiexponential curves suggests that multiple flow compartments are present and, if correlated with the angiogram findings, might suggest that the regional perfusion was mixed.

The answer as to whether or not hemodynamically increased perfusion through the shunt is responsible for relief of symptoms in patients with TIA's is best answered by analysis of middle cerebral artery occlusions. Unfortunately, two of our three patients with this entity showed completed strokes with globally decreased flow through the internal carotid arteries and good flow through the superficial temporal artery, although there was minimal change in their symptoms. The results in the single patient (Case 9) with TIA's suggest, clinically, that hemodynamically decreased flow is responsible since he had recurrence of his symptoms when the anastomosis occluded. Moreover, this patient showed very little flow through his shunt, although it must have supplied the small area in the middle cerebral distribution with critically decreased perfusion. Results in the patients with middle cerebral artery stenosis generally showed that most flow came through the internal carotid system. The finding of similar flow values through both the old and new channels suggested that the flow is determined primarily by the metabolic demand of the tissue. Even though it is ischemic, it is apparently above the threshold for preserving integrated neuronal function. Further information will depend on the analysis of a larger series of patients with TIA's associated with middle cerebral artery occlusions. In addition, the studies suggest that in patients with internal carotid artery occlusion in whom there is demonstration of poor circle of Willis and leptomeningeal collateral circulation, significant flow to the hemisphere can be better obtained by anastomosing two superficial temporal artery branches, rather than one. In middle cerebral artery occlusions and stenoses, the anastomosis can be achieved with one channel, but it should be directed to the area of poorest leptomeningeal collateral as demonstrated angiographically. One would
hope that rCBF studies using small probes similar to the ones in this study could further pinpoint the focal area of ischemia that should be revascularized.

References


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Address reprint requests to: M. Peter Heilbrun, M.D., Division of Neurosurgery, Room 3B 320, University of Utah Medical Center, 50 North Medical Drive, Salt Lake City, Utah 84132.