Changes in Blood Flow and Oxygen Metabolism During Visual Stimulation in Carotid Artery Disease
Effect of Baseline Perfusion and Oxygen Metabolism

Hiroshi Yamauchi, MD, PhD; Hidehiko Okazawa, MD, PhD; Yoshihiko Kishibe; Kanji Sugimoto, MS; Masaaki Takahashi

Background and Purpose—Severe atherosclerotic disease of the carotid arteries may affect perfusion in the posterior circulation according to the degree of collateral supply. The purpose of this study was to determine whether the responses of regional cerebral blood flow (rCBF) and regional cerebral metabolic rate of oxygen (rCMR \text{O}_2) during neural stimulation are affected by the baseline perfusion or oxygen metabolism.

Methods—We used PET to measure rCBF, rCMR \text{O}_2, and regional oxygen extraction fraction (rOEF) in 13 patients with carotid artery steno-occlusive lesions at baseline and during visual stimulation. We examined whether the changes in CBF, CMR \text{O}_2, and OEF during visual stimulation were correlated with the baseline values of these parameters in the visual cortex.

Results—With visual stimulation, rCBF increased in all patients, whereas rCMR \text{O}_2 showed variable changes. The baseline rCMR \text{O}_2 value showed a positive relationship with the degree of rCBF increase and a negative relationship to the degree of rCMR \text{O}_2 increase. rCMR \text{O}_2 decreased in patients with relatively high baseline rCMR \text{O}_2 values, resulting in dissociation of the rCMR \text{O}_2 response from the rCBF response. The rCBF increase was large in the region with an increased baseline rOEF value. These variable changes in rCBF and rCMR \text{O}_2 resulted in a significant correlation between the values of rCBF and rCMR \text{O}_2 during visual stimulation in contrast to the lack of such a correlation at baseline.

Conclusions—In patients with cerebrovascular disease, neural stimulation may induce variable changes in rCBF and rCMR \text{O}_2 according to the baseline perfusion and oxygen metabolism. (Stroke. 2002;33:1294-1300.)

Key Words: carotid artery diseases ■ cerebral blood flow ■ oxygen ■ tomography, emission-computed

During neural stimulation in the normal brain, the increases in regional cerebral blood flow (rCBF) are accompanied by smaller increases in the regional cerebral metabolic rate of oxygen (rCMR \text{O}_2). Consequently, local increases in brain oxygen content occur at the site of activation and provide the basis for the signal used by functional MRI (fMRI). fMRI is increasingly being applied in the investigation of patients with cerebrovascular disease, and the findings suggest its usefulness for monitoring functional changes after stroke. Despite these advances, the relationship between the changes in rCBF and rCMR \text{O}_2 during cerebral activation in cerebrovascular disease is currently not well understood.

Severe atherosclerotic disease of the cerebral arteries results in a reduction of the perfusion pressure in the distal cerebral circulation, which causes changes in rCBF and rCMR \text{O}_2 according to the adequacy of collateral sources of blood flow. A mild reduction in cerebral perfusion pressure causes autoregulatory cerebral vasodilation. With a further reduction in perfusion pressure, the capacity for compensatory vasodilation is exceeded, and rCBF begins to decrease. An increase in the regional oxygen extraction fraction (rOEF) now maintains rCMR \text{O}_2 (misery perfusion). Severe decreases in rCBF lead to focal ischemic changes, which decrease rCMR \text{O}_2 not only in the ischemic region but also in distant regions through deafferentation. Therefore, in patients with cerebrovascular disease, the variation in baseline rCBF, rCMR \text{O}_2, and rOEF is larger than that in normal people, and the effect of this variation on the responses of rCBF and rCMR \text{O}_2 during neural activation is unknown.

Only a few studies have investigated the relationship between the responses in rCBF during activation and the state of the baseline perfusion. It has been speculated that the rCBF response should be absent in regions with increased rOEF, in which autoregulatory cerebral vasodilation may be maximal in response to reduced cerebral perfusion pressure. A study using PET showed that the rCBF response to physiological stimulation was impaired or absent in patients with carotid...
artery disease. The abnormal response in some patients with normal cerebral hemodynamics suggested that hemodynamic disturbance is not the sole determinant of the abnormal rCBF response. When the diseased cerebral arteries perfuse the activated region, the possibility of the abnormal rCBF response caused by ischemic tissue damage of the activated region cannot be excluded completely, which might complicate the interpretation of results. The responses of rCMRO2 during activation in cerebrovascular disease are also largely unknown. Indirectly, a study with near-infrared spectroscopy showed variable oxygen hemoglobin and deoxyhemoglobin responses to language activation in patients with stroke, suggesting the multiplicity of the rCBF and rCMRO2 responses to neuronal activation.10 fMRI studies of normal children have suggested that the degree of increase in rCBF relative to the increase in rCMRO2 during neural activation in the visual cortex may be affected by changes in baseline metabolism during development.11 These studies suggest that changes in baseline perfusion or metabolism in cerebrovascular disease may cause complex changes in rCBF and rCMRO2 during neural activation.

In this study, we used PET to quantitatively measure rCBF and rCMRO2 at rest and during visual stimulation in the visual cortex of patients with carotid artery steno-occlusive lesions, and we examined the relationship of the changes in rCBF and rCMRO2 to the baseline values of these parameters and rOEF. To minimize the effect of direct ischemic tissue damage on the changes of rCBF and rCMRO2 during activation, we selected patients with carotid artery steno-occlusive lesions in whom ischemic damage of the visual cortex is less likely and chose visual stimulation as the neuronal activation task. On the other hand, the visual cortex in these patients may show disturbance is not the sole determinant of the abnormal rCBF response. When the diseased cerebral arteries perfuse the activated region, the possibility of the abnormal rCBF response caused by ischemic tissue damage of the activated region cannot be excluded completely, which might complicate the interpretation of results. The responses of rCMRO2 during activation in cerebrovascular disease are also largely unknown. Indirectly, a study with near-infrared spectroscopy showed variable oxygen hemoglobin and deoxyhemoglobin responses to language activation in patients with stroke, suggesting the multiplicity of the rCBF and rCMRO2 responses to neuronal activation.10 fMRI studies of normal children have suggested that the degree of increase in rCBF relative to the increase in rCMRO2 during neural activation in the visual cortex may be affected by changes in baseline metabolism during development.11 These studies suggest that changes in baseline perfusion or metabolism in cerebrovascular disease may cause complex changes in rCBF and rCMRO2 during neural activation.

In this study, we used PET to quantitatively measure rCBF and rCMRO2 at rest and during visual stimulation in the visual cortex of patients with carotid artery steno-occlusive lesions, and we examined the relationship of the changes in rCBF and rCMRO2 to the baseline values of these parameters and rOEF. To minimize the effect of direct ischemic tissue damage on the changes of rCBF and rCMRO2 during activation, we selected patients with carotid artery steno-occlusive lesions in whom ischemic damage of the visual cortex is less likely and chose visual stimulation as the neuronal activation task. On the other hand, the visual cortex in these patients may show variable degree of perfusion disturbance (changes in rCBF and rOEF) or metabolic decline (changes in rCMRO2) according to the degree of collateral supply from the posterior circulation to the anterior circulation or secondary metabolic depression from ischemic damage in the diseased carotid artery territory. The visual activation used in this study can induce large rCBF and rCMRO2 changes,12 which should be sufficient to permit correlative analysis among the responses. The purpose of this study was to determine whether neural stimulation induces variable changes in rCBF and rCMRO2 according to the baseline perfusion or oxygen metabolism in cerebrovascular disease.

Subjects and Methods

Patients

We studied 13 patients with angiographically documented occlusion or stenosis (≥70% diameter reduction) of the common carotid artery (CCA) or internal carotid artery (ICA). These patients included 9 men and 4 women who were 49 to 78 years of age (mean±SD, 56±9 years). Three patients had no symptoms, 1 had a transient ischemic attack, and 9 had had minor hemispheric stroke with mild disability. All symptoms were related to the affected carotid artery distribution, and no patient had visual symptoms. In the 10 symptomatic patients, the interval between the latest ischemic event and PET evaluations ranged from 1 to 36 months (mean±SD, 12±12 months). All patients had normal visual acuity and visual field. In the asymptomatic patients, arterial disease was suspected because of findings on echo angiograms performed as part of the screening for cerebral arterial disease concomitant with coronary arterial disease. MRI disclosed no cortical infarctions and at most only 1 infarction <1.5 cm in diameter. No abnormality was found in the primary visual cortex or in the white matter corresponding to the optic radiation. In the 3 asymptomatic patients and 1 patient with transient ischemic attack, MRIs were normal. In each of the 9 stroke patients, patchy or confluent high-intensity areas were observed in the affected cerebral white matter on T2-weighted MRI. A smaller degree of abnormality was found on the nonaffected side in 6 patients. Most of these abnormalities were undetectable on T1-weighted MRI, which showed at most only minor subcortical abnormalities in the affected ICA territory. Conventional angiography revealed unilateral ICA occlusion in 4 patients, unilateral extracranial ICA stenosis (75% and 80%) in 2 patients, unilateral CCA stenosis (70%, 80%, and 90%) in 3 patients, bilateral extracranial ICA stenosis (80/70% and 70/50%) in 2 patients, and ICA occlusion with contralateral extracranial ICA stenosis (80% and 50%) in 2 patients. In 3 symptomatic patients with bilateral disease, only the side with more severe vascular lesions was symptomatic.

One patient with ICA occlusion with contralateral ICA stenosis had a left hemispheric stroke from the stenosed ICA. Collateral pathways from the posterior circulation to the anterior circulation were present in 7 patients and included a leptomeningeal anastomosis between the posterior cerebral artery and the middle cerebral artery in 3 patients, a posterior communicating artery in 2, and both in 2. No significant disease of the posterior cerebral artery was seen in any patient. Two patients showed reversal of flow of 1 vertebral artery because of stenosis of the right brachiocephalic artery or the left subclavian artery, but the vertebrobasilar system was angiographically normal in the other 11 patients. The intervals between the conventional angiography and PET studies ranged from 3 to 30 days (mean 18±12 days). In the asymptomatic patients, ICA occlusion was confirmed on angiography ≤1 month before the PET study. Four patients had a history of hypertension, 3 others had a history of diabetes mellitus, and 2 others had a history of both.

We also studied 8 normal volunteers (3 men, 5 women) who were 24±2 years of age (mean±SD) as younger control subjects. These subjects showed normal neurological findings and no specific neurological diseases. None exhibited any abnormal MRI findings, except for a few punctate high-intensity areas in the subcortical white matter on T2-weighted images without corresponding abnormality on T1-weighted images. None of them had hypertension or diabetes mellitus.

PET Measurements

All subjects underwent PET scans with the whole-body Advance PET scanner (General Electric Medical System), which permits simultaneous acquisition of 35 image slices in a 2- or 3-dimensional acquisition mode with interslice spacing of 4.25 mm.14 Written, informed consent was obtained from each subject under the guidance of the Ethics Committee of the Shiga Medical Center. Performance tests showed the intrinsic resolution of the scanner to be 4.6 to 5.7 mm in the transaxial direction and 4.0 to 5.3 mm in the axial direction. As part of the scanning procedure but before the tracer administration, 15O2 transmission scanning was performed for 10 minutes for attenuation correction. For reconstruction of PET data, images were blurred to 6.0-mm full-width half-maximum in the transaxial direction with a Hanning filter. Functional images were reconstructed as 128×128 pixels, with each pixel representing a 2.0×2.0-mm area.

The subjects were positioned in the scanner with their heads immobilized with a head holder and positioned with light beams to obtain transaxial slices parallel to the orbitomeatal line. A small cannula was placed in the left brachial artery for blood sampling. After intravenous bolus injection of 555 MBq of H215O into the right antecubital vein, a 3-minute dynamic PET scan was started at the time of tracer administration with frame durations of 5 seconds for 12 frames, 10 seconds for 6 frames, and 20 seconds for 3 using the 3-dimensional mode. In the oxygen bolus inhalation method, the same procedure of dynamic PET acquisition was started at the time of bolus inhalation of 18O2 at an amount up to 1800 MBq. Arterial blood was continuously drawn from a catheter in the radial artery
with a pump; the concentration of radioactivity was monitored with an in-line flow-through radioactivity detector, the Picocount (Bio-
scan Inc).14; and the concentration of radioactivity was then used as an input function for data analysis. Arterial hematocrit, hemoglobin concentration, PaO₂, and PaCO₂ were also measured. rCBF was calculated by use of the autoradiographic method with a partition coefficient of 0.9 mL/g.15,16 rCMRO₂ was calculated from the dynamic PET data and arterial blood curves by use of the 3-weighted integral method based on a 2-compartment model. The calculation procedure for the 3-weighted integral method has been described in detail elsewhere.17,18 The time delay of arterial input was corrected automatically in the program, and a time constant of τ=4 seconds was used for internal dispersion correction.18 rOEF was calculated from rCBF, rCMRO₂, and arterial O₂ content (CaO₂) as follows: rOEF=rCMRO₂/(rCBF×CaO₂).

Each subject underwent PET scans under 2 conditions: no stimulation (baseline) and visual activation. In the baseline condition, the patients were asked to fixate on a crosshair in the center of the screen 30 seconds before the scan and throughout the subsequent 3-minute scan. In the activation condition after baseline scans, the patients were shown a yellow-blue annular checkerboard whose contrast was reversed at a frequency of 4 Hz, which may cause a maximum change in PET variables during visual stimulation.19 Stimulation began 4 minutes before the start of the dynamic PET scan and continued for a total of 7 minutes. There was a time gap of at least 15 minutes between scans.

Data Analysis
We analyzed 10 tomographic planes from 46.25 to 84.5 mm above and parallel to the orbitomeatal line, which correspond to the levels of the basal ganglia and thalamus to the centrum semiovale. The hemisphere supplied by the diseased carotid artery in patients with unilateral vascular disease or the hemisphere supplied by the more severely diseased carotid artery in patients with bilateral vascular disease was referred to as the ipsilateral hemisphere. The region of interest (ROI) was placed on the CBF images during visual activation. According to the atlas prepared by Kretschmann and Weinrich,20 the lower 3 images were examined by placing a total of 2 circular 16-mm-diameter ROIs compactly over the gray matter of the medial occipital cortex in each hemisphere along the posteroanterior direction from the posterior end. These ROIs included the perical-
carne visual cortex and adjacent visual association cortex of the medial side. The same ROIs were transferred to the CBF and CMRO₂ images at baseline and the CBF images during activation. The regional values in the visual cortex of the ipsilateral or contralateral hemisphere were calculated as the average for all ROIs in each hemisphere. In control subjects, the mean value in the bilateral visual cortices was calculated as the average for all ROIs in both hemi-
spheres. In addition, all 10 images were examined by placing a total of 10 to 12 circular 16-mm-diameter ROIs compactly over the gray matter of the outer cortex in each hemisphere.21 The averaged values in all ROIs in the bilateral hemispheres, including the visual cortex ROIs, were referred to as the global values and were used for normalization of values during visual stimulation to negate the effect of fluctuations in whole-brain values.

We corrected the rCBF, rCMRO₂, and rOEF values in the visual cortex during activation by dividing by the correction factor of each variable: global values (activation)/global values (baseline). We calculated the percentage difference between the corrected values obtained during activation and the values at baseline (Δ%) as follows: Δ%=[(corrected rCBF or rCMRO₂ value (activation)−rCBF or rCMRO₂ value (baseline))×100 (%). We assumed that the resulting values reflected the percent changes caused by visual stimulation.

Statistical Analysis
We compared the values of the PET variables or the physiological data obtained at baseline and during activation using the paired t test. Baseline values and the changes in PET variables obtained in the patients were compared with those obtained in control subjects through 1-way analysis of variance and post hoc Scheffé’s analysis. Significance was established at P<0.05. We analyzed the relation between the change in 1 PET variable and 3 baseline PET parameters (rCBF, rCMRO₂, and rOEF) using linear regression analysis; statistical significance was accepted at P<0.016 (0.05/3) by use of a Bonferroni correction to reduce type 1 error resulting from the multiplicity of correlations tested.

Stepwise multiple linear regression analysis was used to test the independent predictive value of baseline hemodynamic or metabolic parameters on the change of the PET variables during activation. We applied this analysis to the hemispheric values of the fractional change in PET variables as the dependent variable and the value of baseline PET parameters, including rCBF, rCMRO₂, and rOEF, as the independent variables. We adopted data pairs from the 2 hemispheres for each patient because of the suspected hemispheric difference in baseline hemodynamics and metabolism, depending on the severity of arterial disease in each patient, although the data are not independent of each other. In addition, the values of rCBF, rCMRO₂, and rOEF are not strictly independent.

Results
Control Subjects
There was no significant difference in the physiological data obtained in the control subjects during PET scanning at baseline and during visual stimulation, except for a slight decrease in mean arterial blood pressure (Table 1). The values of the correction factor [global value (activation)/global value (baseline)] for CBF, CMRO₂, and OEF were 0.99±0.04, 1.00±0.07, and 1.01±0.05 (mean±SD), respectively. There was no significant difference in global CBF, CMRO₂, or OEF between the baseline and activated conditions.

During visual stimulation, the rCBF values in the visual cortex increased in all patients (mean increase, 28%;
All but 1 patient showed an increase in rCMR O 2 values (mean increase, 4%; \( P < 0.05 \)). The rOEF values were decreased in all patients (mean decrease, 18%; \( P < 0.001 \)). The change in rCMR O 2 was significantly and negatively correlated with the baseline value of rCMR O 2 (\( r = 0.85, P < 0.01 \)).

A significant correlation was found between the values of rCMR O 2 and rCBF in the visual cortex at baseline (\( r = 0.79, P < 0.01 \)), although there was no such correlation during visual stimulation (\( r = 0.45, P = 0.26 \)). A significant negative correlation was found between the changes in rOEF and rCBF (\( r = -0.86, P < 0.01 \)).

Patients

There was no significant difference in the physiological data obtained in patients during PET scanning at baseline and during visual stimulation, except for slight increases in \( \text{PaO}_2 \) and \( \text{CaO}_2 \) (Table 1). The values of the correction factor

### TABLE 2. Baseline and Activation Values of PET Variables in the Visual Cortices Ipsilateral and Contralateral to the More Severe Carotid Artery Disease

<table>
<thead>
<tr>
<th>Variable</th>
<th>Conditions</th>
<th>Hemisphere</th>
<th>Baseline</th>
<th>Activation</th>
<th>Percent Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>rCBF, mL ( \cdot 100 \text{ g}^{-1} \cdot \text{min}^{-1} )</td>
<td>Ipsilateral</td>
<td>43.0±5.1</td>
<td></td>
<td>49.2±6.9†</td>
<td>14.5±10.7§</td>
</tr>
<tr>
<td></td>
<td>Contralateral</td>
<td>43.0±5.8</td>
<td></td>
<td>50.3±6.6‡</td>
<td>17.5±11.1</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>52.1±3.2</td>
<td></td>
<td>66.6±6.0‡</td>
<td>28.0±9.0</td>
</tr>
<tr>
<td>rCMRO 2, mL ( \cdot 100 \text{ g}^{-1} \cdot \text{min}^{-1} )</td>
<td>Ipsilateral</td>
<td>4.65±0.52§</td>
<td></td>
<td>4.82±0.35</td>
<td>4.1±4.4</td>
</tr>
<tr>
<td></td>
<td>Contralateral</td>
<td>4.74±0.44</td>
<td></td>
<td>4.81±0.37</td>
<td>1.8±5.8</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>5.25±0.58</td>
<td></td>
<td>5.45±0.43*</td>
<td>4.4±4.6</td>
</tr>
<tr>
<td>rOEF, %</td>
<td>Ipsilateral</td>
<td>62.1±7.0</td>
<td></td>
<td>55.6±6.4†</td>
<td>−9.8±10.4</td>
</tr>
<tr>
<td></td>
<td>Contralateral</td>
<td>63.5±7.8</td>
<td></td>
<td>54.3±6.9‡</td>
<td>−14.2±7.0</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>59.5±6.3</td>
<td></td>
<td>48.9±7.3‡</td>
<td>−18.1±6.4</td>
</tr>
</tbody>
</table>

Values are mean±SD. The values of rCBF, rCMRO 2, and rOEF during activation were corrected by dividing by the correction factor of each variable: global value (activation)/global value (baseline).

\( *P<0.05, †P<0.01, ‡P<0.001 \) vs baseline (paired t test).

\( §P<0.05, ||P<0.005 \) vs control (1-way analysis of variance and post hoc Scheffe’s analysis).

P<0.001; Table 2). All but 1 patient showed an increase in rCMRO 2 values (mean increase, 4%; \( P < 0.05 \)). The rOEF values were decreased in all patients (mean decrease, 18%; \( P<0.001 \)). The change in rCMRO 2 was significantly and negatively correlated with the baseline value of rCMRO 2 (\( r = -0.85, P < 0.01 \)).

A significant correlation was found between the values of rCMRO 2 and rCBF in the visual cortex at baseline (\( r = 0.79, P < 0.01 \)), although there was no such correlation during visual stimulation (\( r = 0.45, P = 0.26 \)). A significant negative correlation was found between the changes in rOEF and rCBF (\( r = -0.86, P < 0.01 \)).
tended to be larger in regions with higher rOEF values ($r=0.45$, $P=0.13$). The change in rCMRO$_2$ was significantly and negatively correlated with the baseline value of rCMRO$_2$ ($r=-0.80$, $P<0.002$; Figure 2). A significant negative correlation was found between the change in rOEF and the baseline value of rCMRO$_2$ ($r=-0.80$, $P<0.002$). Similar correlations were found in the contralateral visual cortex.

When the baseline values of rCBF, rCMRO$_2$, and rOEF from the 2 hemispheres of each patient were entered into a stepwise multiple linear regression analysis, the baseline values of rCMRO$_2$ accounted for a significant proportion of the variance of change in rCBF ($P<0.05$, adjusted $R^2=0.12$), rCMRO$_2$ ($P<0.0001$, adjusted $R^2=0.49$), and rOEF ($P<0.0001$, adjusted $R^2=0.48$) during activation; the other variables did not significantly add to the magnitude of these $R^2$ values.

When the values from the 2 hemispheres of each patient were analyzed, a significant correlation was found between rCMRO$_2$ and rCBF in the visual cortex during visual stimulation ($r=0.50$, $P=0.01$), although there was no such correlation at baseline ($r=0.21$, $P=0.29$). A significant negative correlation was found between the changes in rOEF and rCBF ($r=-0.80$, $P<0.0001$).

**Discussion**

This study showed that in patients with cerebrovascular disease, neural stimulation induces variable changes in rCBF and rCMRO$_2$ according to the baseline perfusion and oxygen metabolism. In the visual cortex in patients with carotid artery steno-occlusive lesions, visual stimulation increased rCBF in all patients. The degree of increase in rCBF in patients was decreased in the visual cortex ipsilateral to the more severe carotid artery disease compared with the degree of increase in younger control subjects and was positively correlated with the baseline rCMRO$_2$ value. The decreased rCBF response was associated not with an increase but with a decrease in baseline rOEF value (an index of perfusion disturbance). On the other hand, rCMRO$_2$ showed variable changes among patients. The degree of increase in rCMRO$_2$ did not differ between patients and control subjects and was negatively correlated with baseline rCMRO$_2$ value in both patients and control subjects. rCMRO$_2$ decreased in patients with relatively high baseline rCMRO$_2$ values and increased in patients with low rCMRO$_2$ values. Thus, dissociation of the rCMRO$_2$ response from the rCBF response occurred in some patients. In patients, these variable changes in rCBF and rCMRO$_2$ resulted in a significant correlation between the values of rCBF and rCMRO$_2$ during visual stimulation in the visual cortex, although there was no such correlation at baseline.

It has been speculated that the rCBF response should be absent in regions with increased rOEF, in which autoregulatory cerebral vasodilation may be maximal in response to reduced cerebral perfusion pressure. In this study, however, visual stimulation increased rCBF in the visual cortex in all patients studied. Furthermore, the increase in rCBF tended to be larger in the region showing increased rOEF at baseline, in contradiction to the speculation. In the patients studied, the increased baseline rOEF may have been caused by carotid artery disease because the visual cortexes in patients with...
severe bilateral carotid artery diseases had a higher rOEF than in patients with unilateral disease. In patients with bilateral disease of the carotid artery, blood flowing through the basilar artery will be redistributed via the posterior communicating arteries and leptomeningeal vessels to compensate for reduced flow in the anterior circulation, resulting in reduced flow in the visual cortex. Therefore, in cerebrovascular disease, neural stimulation can induce an rCBF response, the degree of which does not necessarily decrease because of perfusion disturbance. Indeed, decreased rCBF relative to rCMRO₂ (increased rOEF), if the rCMRO₂ is preserved, may even increase the degree of the rCBF response. Our results are consistent with those of an earlier PET study that showed reduced rCBF responses to physiological stimulation of the sensorimotor cortex independent of baseline hemodynamic disturbance in some patients with severe carotid artery disease in whom rCMRO₂ might be decreased. The rCBF response was decreased only in the visual cortex ipsilateral to the more severe carotid artery disease, where the baseline rCMRO₂ value was decreased compared with that in younger control subjects. This is probably the result of secondary metabolic depression from ischemic damage in the region of the carotid artery distribution or, less likely, primary ischemic changes, although other factors, including age and vascular risk factors, may contribute to the bilateral decrease in baseline rCMRO₂. A recent PET study showed that in unilateral major cerebral arterial occlusive diseases, rCBF increased in both hemispheres with bimanual activation, but only in the contralateral hemisphere with acetazolamide, suggesting that neural activation can induce a nearly normal rCBF response in brains with preexisting vasodilation. It is speculated that the mechanism of vasodilation responsible for activation-induced rCBF change may be different in part from the mechanism of autoregulatory vasodilation. Different mediators or different sizes of arteries may contribute to vasodilation in these 2 conditions. Taken together, these findings indicate that rCBF can increase in response to neural activation in the presence of autoregulatory vasodilation, and an increase in rCBF can be used as a qualitative index of local neuronal activity in cerebrovascular disease.

We made the surprising findings here that the rCMRO₂ response to visual stimulation was negatively associated with baseline rCMRO₂ and that the rCMRO₂ decreased in patients with relatively high baseline rCMRO₂ and increased in patients with low rCMRO₂, although an increase in rCBF suggested increased neuronal activity in all patients. The rCMRO₂ response during neural activation may be affected by the baseline oxygen metabolism and may be dissociated from the rCBF response in cerebrovascular disease. fMRI studies in normal children have suggested that the increase in rCBF relative to the increase in rCMRO₂ during neural activation is dependent on the baseline metabolism. A decrease in rCMRO₂ with an increase in rCBF during activation, which has been reported in a few normal subjects, has not been shown in patients with cerebrovascular disease. However, a study with near-infrared spectroscopy showed a large decrease in deoxyhemoglobin during language activation in some patients with cerebrovascular disease, which might suggest a decrease in rCMRO₂ during neuronal activation. The reason for the rCMRO₂ decrease during activation is unclear. However, a significant correlation between the values of rCMRO₂ and rCBF in the visual cortex was absent at baseline but present during visual stimulation, suggesting that variable changes in rCBF and rCMRO₂ might be induced during activation to attain a certain relationship between rCBF and rCMRO₂ in the activated brain region. Therefore, one possible explanation for the rCMRO₂ decrease is that a change in some metabolic components during activation may induce the rCMRO₂ decrease. The primary metabolic change associated with increases in neuronal activity may be an increase in nonoxidative glucose metabolism, which may occur in patients with a decrease in rCMRO₂ during neural stimulation in this study. In patients with relatively high baseline rCMRO₂, a certain portion of the oxidative metabolism of glucose occurring at baseline might change into nonoxidative metabolism on stimulation, which may produce an efflux of lactate into the blood circulation without oxygen consumption, leading to a decrease in rCMRO₂. Further studies, including measurements of regional glucose metabolism or definitive measurements of neuronal activity, are required to test this hypothesis.

The bolus method for rCMRO₂, used in this study, allows repetition of the measurements every 10 minutes. This method is considered ideal for repeated measurement of rCMRO₂ before and after cerebral activation to see the effect of activation. However, this method may overestimate rCMRO₂ and consequently rOEF in the brain region near the major veins and sinuses. This may be true in the visual cortical region analyzed in this study. Although blood volume was estimated and extracted as a separate parameter in this method, the radioactivity resulting from unextracted ¹⁵O₂ in the venous blood may not be excluded sufficiently. To obtain precise rCMRO₂ and rOEF values with this bolus method, correction for the intravenous unextracted ¹⁵O₂ may be needed. In patients with carotid artery disease, the value of blood volume in the visual cortex may differ according to the degree of autoregulatory vasodilation, and this variation in itself may lead to variation in baseline rCMRO₂ values. The large rCBF increase, probably with a large increase in blood volume, in patients with a rCMRO₂ decrease may eliminate the possibility that an inadequate correction for the intravenous unextracted ¹⁵O₂ caused the rCMRO₂ decrease. However, possible errors in rCMRO₂ measurement might be caused by changes in blood volume and rCBF between baseline and activation, because rCMRO₂, rCBF, and blood volume are dependent on each other in the O₂ bolus inhalation method. Therefore, we cannot completely exclude the possibility that methodological problems may have led to the negative relationship between rCMRO₂ response and baseline rCMRO₂ value.

The multiplicity of rCBF and rCMRO₂ responses to neuronal activation shown in this study has some implications for fMRI studies, with the assumption that similar changes occur after other kinds of stimulation in other cortical areas. Most fMRI studies are based on the blood oxygen level–dependent (BOLD) contrast caused by alterations in local deoxyhemoglobin content, which is indexed by changes in rOEF when Cao₂ is constant. A decrease in rOEF during activation is
associated with an increased BOLD signal. The present study showed that the degree of decrease in rOEF during activation was correlated with the degree of increase in CBF, suggesting that the BOLD signal change can be used as a qualitative index of the rCBF response in cerebrovascular disease. This finding is in agreement with the similarities in activation patterns among PET and fMRI measurements in previous studies and supports the idea that fMRI can be applied to the study of functional localization after stroke. However, the dependence of the decrease in rOEF on baseline rCMRO₂ values suggests that the change in baseline oxygen metabolism in stroke patients may affect the degree of BOLD signal change during activation. Thus, caution should be exercised in the interpretation of the change in BOLD signal during activation as a quantitative index of the functional change after stroke.

In conclusion, in patients with cerebrovascular disease and normal visual function, neural stimulation induces an increase in rCBF in the visual cortex regardless of the severity of perfusion disturbance. This supports the idea that functional imaging methods of brain activation can be applied to the study of functional localization after stroke. However, the dissociation of the change in rCMRO₂ from the change in rCBF, which may depend on baseline rCMRO₂, should be kept in mind when changes in rCBF and rCMRO₂ are used as quantitative indexes of brain function. Our quantitative data will be useful for the interpretation of the results obtained from other qualitative functional imaging methods in cerebrovascular disease.

Acknowledgments

We thank the staff of the PET Unit, Research Institute, Shiga Medical Center for support and technical help. We also appreciate the clinical assistance of the staff of the Department of Neurology and Department of Neurosurgery, Shiga Medical Center.

References

Changes in Blood Flow and Oxygen Metabolism During Visual Stimulation in Carotid Artery Disease: Effect of Baseline Perfusion and Oxygen Metabolism
Hiroshi Yamauchi, Hidehiko Okazawa, Yoshihiko Kishibe, Kanji Sugimoto and Masaaki Takahashi

Stroke. 2002;33:1294-1300
doi: 10.1161/01.STR.000014505.73536.B4
Stroke is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2002 American Heart Association, Inc. All rights reserved.
Print ISSN: 0039-2499. Online ISSN: 1524-4628

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://stroke.ahajournals.org/content/33/5/1294

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in Stroke can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Stroke is online at:
http://stroke.ahajournals.org/subscriptions/