Vascular Response to Carbon Dioxide in Areas With and Without Diaschisis in Patients With Small, Deep Hemispheric Infarction

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The reactivity of cerebral blood vessels to changes in Paco₂ in areas of the cerebral cortex with or without diaschisis was investigated in 13 patients in a subacute or chronic stage after a small capsular infarct. A focal area of hypoperfusion (area of diaschisis) was detected in the ipsilateral sensorimotor cortex in each patient. Hyperventilation caused a significant reduction of regional cerebral blood flow in the area without diaschisis and only a tendency for regional cerebral blood flow to decrease in the area with diaschisis; CO₂ inhalation induced a slight increase in regional cerebral blood flow in the area without diaschisis and a significant increase in regional cerebral blood flow in the area with diaschisis. Regional cerebral blood flow reactivity to hypocapnia was significantly less in the area with diaschisis than in the area without, whereas the hypercapnic response was more marked in the area with diaschisis than in the area without. Our results suggest that in the area with diaschisis, the arterioles may be abnormally vasoconstricted at rest such that they cannot constrict further in response to hypocapnia but can dilate more during hypercapnia than in the area without diaschisis. This excessive resting vasoconstriction may result from decreased tissue elaboration of CO₂ due to local decrease of metabolic function. (Stroke 1988;19:840–845)

The concept that a local brain lesion could cause a transient depression of function in structurally normal areas distant from, but connected to, the originally involved site was called "diaschisis" by von Monakow. Pertinent observations have been reported, with additional documentation from advances in measurements of cerebral blood flow (CBF) and metabolism. The occurrence of interhemispheric diaschisis, intrahemispheric diaschisis, or crossed cerebellar diaschisis in different distant sites following a hemispheric infarction is now well established. The manifestations of these clinical entities have been attributed to the depression of neural function in other brain regions linked to the infarcted area and have been demonstrated to be hypometabolic regions.

The last decade, the use of positron emission tomography (PET) to study stroke has confirmed the original observation relating to diaschisis. Several studies have investigated the relations among blood flow, oxygen metabolism, and glucose utilization and have demonstrated the proportional and parallel reductions in CBF and metabolism in the hemisphere or cerebellum contralateral to that in which diaschisis is manifested. Only a few reports have described the characteristics of the cerebral blood vessels in the area of diaschisis. The cerebral vascular tone or resistance and the vascular response to changes in mean arterial blood pressure (MABP) or arterial carbon dioxide tension (Paco₂) remain unclear.

In our preliminary study, we reported on the cerebral vascular tone in the ipsilateral cerebral cortex, in which a small infarct in the internal capsule manifested a focal area of hypoperfusion. The purpose of our current study is to investigate the reactivity of cerebral blood vessels to Paco₂ changes in areas of the cerebral cortex both with and without diaschisis, which result from a small, deep capsular infarct.
Subjects and Methods

We studied 13 patients who suffered from mild or moderate hemiparesis after cerebral infarct and showed a small capsular infarct diagnosed as a hypodense lesion on computed tomography (CT scan). Informed consent was obtained from each subject before the initiation of the study in accordance with the Helsinki Declaration of 1975. Regional CBF (rCBF) was measured in all patients using the \( ^{133} \text{Xe} \) intra-arterial injection method. The size of the low-density capsular lesion was determined by measuring the diameter (mm) on the numeric printout of the CT scan. rCBF with subjects in the resting state ranged from 2.56 to 8.96 cm\(^2\). No occlusive lesion was detected in the intracranial or extracranial arteries on serial cerebral angiograms. The details of these findings are presented in Table 1.

Measurement of Regional Cerebral Blood Flow

A small catheter was inserted into an internal carotid artery, and an Anger-type gamma camera (Dyna Camera 3C, Picker International, Inc., Cleveland, Ohio) was placed over the lateral (12 patients) or the ventral (one patient) aspect of the head. Arterial blood was sampled anaerobically, and arterial blood gases were analyzed using an automatic gas analyzer (model 175, Corning Glass Works, Corning, New York). Approximately 4 mCi of \( ^{133} \text{Xe} \) in 2 ml saline was injected rapidly through the catheter. The \( \gamma \)-rays were measured in 5-second periods successively for 130 seconds, processed into digital images on a \( 64 \times 64 \) matrix of \( 4 \times 4 \) mm\(^2\) elements by an RI data processor (EDR-4200, Hitachi Medical Corp.), and recorded on magnetic tape. Arterial blood pressure was measured periodically with a mercuric manometer before and during this measurement. After \( \geq 15 \) minutes, 11 patients were hyperventilated and six inhaled a 5% CO\(_2\)-air mixture through a mask for 5 minutes, during which time rCBF was measured again by injecting the same dose of \( ^{133} \text{Xe} \) (immediately after collection of arterial blood for gas analysis) 3 minutes after the start of hyperventilation or CO\(_2\) inhalation. Thereafter, angiography was carried out through the same catheter. For each rCBF measurement in these CO\(_2\) manipulation studies, background activity was subtracted.

Functional Image

The rCBF functional image was made up from the data recorded on the magnetic tape, as described elsewhere,\(^1\) and only a brief outline is given here. Data were processed in a \( 32 \times 32 \) matrix arranged from the \( 64 \times 64 \) matrix. Accordingly, a unit region containing areas of the gamma camera matrix that were not oriented toward the brain (e.g., the edge of the head), we defined the processing area as unit regions that had \( >30\% \) of the maximum count around the center of the accumulated image in the initial 10 frames after the injection of \( ^{133} \text{Xe} \). In our
Table 2. rCBF and Size of Capsular Infarct in 13 Patients

<table>
<thead>
<tr>
<th>Low-density area on computed tomogram</th>
<th>rCBF (ml/100 g/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Area without diaschisis</td>
</tr>
<tr>
<td>≤10 mm</td>
<td>50 ± 6</td>
</tr>
<tr>
<td>&gt;10 mm</td>
<td>40 ± 4*</td>
</tr>
</tbody>
</table>

rCBF, regional cerebral blood flow. Patients were divided into groups according to largest diameter of low-density area presented in Table 1.

*p<0.01, †p<0.05 (unpaired t test) significantly different from mean rCBF in patients with smaller infarct.

previous report, by superimposing the data processing area on 99mTc-brain scintigrams performed simultaneously, we confirmed that we could successfully delete the areas that were not oriented toward the brain. rCBF was calculated at every unit region in this data processing area by the initial slope method, and 0.87 was used as the 133Xe brain–blood partition coefficient. rCBF values for the corresponding unit regions were displayed on a cathode-ray tube as a gray map, with brightness modulation as the functional image. Numerical rCBF values in a map format were also displayed.

Data Analysis

Mean CBF (CBF) was determined from rCBFs in all regions. To find interregional differences in blood flow, the percent relative flow in each region was calculated as (rCBF − CBF)/CBF × 100. The regional variation in the rCBF functional image of controls without intracranial diseases, expressed as standard deviation (SD), was 7%. Therefore, in our present study, the region with a relative flow of less than −15% (>2 × SD) was defined as the area of hypoperfusion. As reported, a focal hypoperfusion area was observed in all patients and localized around the central sulcus, and this focal hypoperfusion area was defined as the “area of diaschisis”. CBF in this hypoperfusion area in the resting state was thus defined as rCBF in the area with diaschisis, and CBF in the remaining area of the rCBF functional image was defined as rCBF in the area without diaschisis.

As serial images were measured at the same position during hyperventilation or CO₂ inhalation as in the resting state, regional hemodynamic changes could be analyzed by comparing rCBF of the same unit region in functional images before and after the test. The relations between blood flow and cerebral perfusion pressure in the brain regions were assessed by calculating cerebrovascular resistance (CVR) as MABP/rCBF, mm Hg/ml/100 g/min, with MABP used instead of the cerebral perfusion pressure. The Paco₂−rCBF relations were assessed by calculating the reactivity of cerebral vessels to CO₂, as ΔrCBF/ΔPaco₂, ml/100 g/min/mm Hg. The value was positive if rCBF changed in the same direction as Paco₂; if the changes were in opposite directions, it was negative.

Results

There were no clear relations between interval from ictus to the rCBF measurement, the size of infarction on CT scan, the resting Paco₂, and the extent of areas with or without diaschisis. On the contrary, significant decreases of rCBF in areas both with and without diaschisis (p < 0.01, p < 0.05, respectively) were noted in patients with large infarcts compared with patients with smaller ones (Table 2).

Hemodynamic changes induced by hyperventilation in 11 patients are shown in Table 3. Following a short period of hyperventilation, MABP changed variably in each patient. The overall mean change of MABP was a slight nonsignificant decrease. Various reductions of Paco₂ were achieved in individual patients by this procedure, and mean ± SD Paco₂ decreased significantly (p < 0.001), from 39 ± 4 to 32 ± 4 mm Hg. The global significant reduction of rCBF in the large area without diaschisis was seen in all patients, and mean ± SD rCBF decreased significantly (p < 0.001) from 44 ± 6 to 33 ± 7 ml/100 g/min. However, small decreases of rCBF in seven of the 11 patients, no change in one patient, and even an increase of rCBF in the remaining three patients were seen in the small area with diaschisis. Mean rCBF in the area with diaschisis decreased slightly (not significant). The area with diaschisis observed in the resting rCBF functional image disappeared in eight of the 11 patients upon hyperventilation. Aside from these, there were no regions with relative flow of less than −15% in the functional image during hyperventilation.

Table 3. Effect of Hyperventilation and CO₂ Inhalation in Patients With Small Capsular Infarcts

<table>
<thead>
<tr>
<th></th>
<th>MABP (mm Hg)</th>
<th>Paco₂ (mm Hg)</th>
<th>rCBF (ml/100 g/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td></td>
<td>Area without diaschisis</td>
</tr>
<tr>
<td>Resting state</td>
<td>11</td>
<td>112 ± 12</td>
<td>39 ± 4</td>
</tr>
<tr>
<td>Hyperventilation</td>
<td>11</td>
<td>110 ± 7</td>
<td>32 ± 4†</td>
</tr>
<tr>
<td>Resting state</td>
<td>6</td>
<td>122 ± 18</td>
<td>38 ± 2</td>
</tr>
<tr>
<td>CO₂ inhalation</td>
<td>6</td>
<td>118 ± 8</td>
<td>41 ± 2‡</td>
</tr>
</tbody>
</table>

MABP, mean arterial blood pressure; Paco₂, arterial carbon dioxide tension; rCBF, regional cerebral blood flow. Values are mean ± SD.

* p<0.001, †p<0.05 (paired t test) significantly different from mean in area without diaschisis.

†p<0.001, ‡p<0.01 (paired t test) significantly different from mean of corresponding resting state.
TABLE 4. Cerebrovascular Resistance in Areas With or Without Diaschisis

<table>
<thead>
<tr>
<th>Cerebrovascular resistance (mm Hg/ml/100 g/min)</th>
<th>Area without diaschisis</th>
<th>Area with diaschisis</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resting state 11</td>
<td>2.59 ± 0.51</td>
<td>3.41 ± 0.91*</td>
</tr>
<tr>
<td>Hyperventilation 11</td>
<td>3.46 ± 0.84t</td>
<td>3.87 ± 1.42</td>
</tr>
<tr>
<td>Resting state 6</td>
<td>2.70 ± 0.47</td>
<td>3.38 ± 0.64*</td>
</tr>
<tr>
<td>CO2 inhalation 6</td>
<td>2.25 ± 0.53</td>
<td>2.44 ± 0.48†</td>
</tr>
</tbody>
</table>

Values are mean ± SD.
*p<0.01, †p<0.05 (paired t test) significantly different from mean in area without diaschisis.
*tp<0.01 (paired t test) significantly different from mean of corresponding resting state.

As also shown in Table 3, CO2 inhalation variously changed MABP in each patient. Mean MABP changes were not significant. Although the elevation of PaCO2 was small in some patients who were anxious during CO2 inhalation and who might have had a leak from the mask in the gas administering system, a significant increase in PaCO2 was induced, from 38 ± 2 mm Hg in the resting state to 41 ± 2 mm Hg during CO2 inhalation. The overall rCBF increased in the area without diaschisis in all six patients, whereas the elevation of the mean was not significant. rCBF in the area with diaschisis increased remarkably without exception. Mean ± SD rCBF changed significantly (p<0.01), from 37 ± 8 to 50 ± 12 ml/100 g/min. The area with diaschisis remained in the rCBF functional image of one of the six patients during CO2 inhalation.

CVR in the areas with and without diaschisis before and after hyperventilation and CO2 inhalation is shown in Table 4. In the resting state, CVR in the area with diaschisis was significantly (p<0.01) greater than in the area without diaschisis. In 11 patients, hyperventilation elevated CVR in both areas, but significant increase was noted only in the area without diaschisis. In six patients, CO2 inhalation reduced CVR in both areas, but significant reduction of CVR was observed only in the area with diaschisis.

Table 5 shows the index for cerebral vascular reactivity to CO2 in the areas with and without diaschisis by functional activation with hyperventilation or CO2 inhalation. On hyperventilation in 11 patients, the change in rCBF per unit reduction of PaCO2 was significantly greater in the area without diaschisis than in the area with diaschisis. The index was positive in the area without diaschisis in all 11 patients, whereas in the area with diaschisis the index was positive in seven of 11, 0 in one, and negative in the other three patients. With CO2 inhalation in six patients, the index was positive in both areas in all patients. The mean index was smaller in the area without diaschisis than in the area with diaschisis, though this difference was not significant.

TABLE 5. Cerebral Vascular Reactivity to CO2 in Areas With or Without Diaschisis

<table>
<thead>
<tr>
<th>Cerebrovascular reactivity index (ml/100 g/min/mm Hg)</th>
<th>Area without diaschisis</th>
<th>Area with diaschisis</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hyperventilation 11</td>
<td>1.68 ± 0.56</td>
<td>0.64 ± 1.35*</td>
</tr>
<tr>
<td>CO2 inhalation 6</td>
<td>2.70 ± 2.82</td>
<td>4.33 ± 1.56</td>
</tr>
</tbody>
</table>

Values are mean ± SD change in regional cerebral blood flow divided by change in arterial carbon dioxide tension.
*p<0.01 (paired t test) significantly different from mean in area without diaschisis.

Discussion

A normal brain has the intrinsic ability for the cerebral blood vessels to alter their caliber to maintain a constant blood flow with variations in blood pressure. At the same time, normal cerebral tissue has the means for dynamic regulation of blood flow in accordance with regional metabolic demands depending on neural activity. Such regulation of cerebral circulation is at least in part mediated by the products of cerebral metabolism. CO2, a metabolic product, affects blood flow in the brain as a whole, regionally altering the resistance of the cerebral vessels. The capacity of the vessels to dilate when PaCO2 increases and to constrict when it decreases (i.e., chemical control) is reflected in the change in CBF for a given change in PaCO2. Many structural and functional components in the brain operate under these conditions of cerebral circulation and cooperate with each other through neural pathways to maintain integrated function of the central nervous system. If damage occurs in one part of the brain, lack of normal afferent input may induce a neural hypoactivity in the target structures. The longer such a condition remains, the more likely will regulation of the cerebral circulation be disturbed, possibly resulting in morphologic alterations. Therefore, it seems of interest to investigate whether such chemical control is disturbed in the brain regions in which diaschisis occurs. In our study, 13 patients with small capsular infarcts were investigated in a subacute or chronic stage, when intrahemispheric diaschisis is observed.

There are several methods for studying regional blood flow or metabolic function in the brain. Our current data for rCBF was obtained by the 133Xe intracarotid injection method. This approach necessitates puncture of the carotid artery and usually restricts CBF examination to the carotid artery territory in one hemisphere. Reliability of the rCBF values in areas of the lesion remains uncertain because the calculation depends on the 133Xe brain-blood partition coefficient, which may change in injured tissue. rCBF values in injured tissue may be partially averaged with those in more normal, adjacent tissues. However, the limitations mentioned above did not interfere with application of this technique to our patients because our aim was to...
obtain information on the cortical circulation in the infarcted hemisphere. Such information was available with the two-dimensional $^{133}$Xe method. The small size and shallow depth of the infarcted area made it possible to disregard regional differences of the $^{133}$Xe partition coefficient and a "look-through" artifact. With intracarotid injection of $^{133}$Xe, a high count rate could be reached to obtain high spatial resolution so that the rCBF functional images appeared to have high enough accuracy in the clinical diagnosis. 15 Our system adopted the initial slope method to calculate rCBF, which made it suitable to observe hemodynamic changes by various physiologic tests.

In our study, we showed significant differences between cerebrovascular reactivity to PCO2 changes in the areas of cerebral cortex with and without diaschisis, independent of the accompanying changes in systemic blood pressure. The mechanism of chemical control of rCBF in the territory without diaschisis appeared close to normal, whereas the reactivity of blood vessels to CO2 changes seemed abnormal in the area with diaschisis. It has been suggested that bilateral reduction of CBF in patients with unilateral infarction may be caused by a diffuse increase in CVR. 12, 13 As presented in Table 4, in the ipsilateral hemisphere CVR in the resting state was significantly greater in the area with diaschisis than in the area without diaschisis. Using the $^{133}$Xe intracarotid injection method in patients with ischemic cerebrovascular disease, Ackerman et al 19 examined the rCBF response to hypocapnia induced by hyperventilation in the ipsilateral hemisphere. They found that a positive linear correlation was demonstrated between CO2 reactivity and conductance (the reciprocal of resistance). We found that the higher the initial CVR, the smaller the change in CVR, which made it suitable to observe hemodynamic changes by various physiologic tests.

When cerebral perfusion pressure changes, arterioles with a diameter of $\geq 50 \mu$m act under nervous control while those with a smaller diameter act under chemical control in proportion to the level of local metabolism, thus balancing each other to regulate local circulation. 20, 21 Contrary to our results, Fujishima et al 22 reported that the lower the cerebral oxygen consumption, the lower the capacity of cerebral vessels to dilate in response to a PaCO2 increase. It seems that the difference depends on the degree of pathologic damage in the brain tissue in which CO2 reactivity is assessed. 23 They assessed reactivity in the whole hemisphere, which contained the infarcted lesion, whereas we studied structurally normal brain tissue. On the other hand, Wise et al 24 described in a PET study that, in spite of sufficient availability, both oxygen and glucose consumption in the corresponding regions of the contralateral hemisphere (where diaschisis is believed to occur) are slightly lower than those of normal controls. The low consumption of oxygen and glucose may lead to a reduction of CO2 production in the area affected by diaschisis. In these areas, arterioles may hence tend to constrict, limiting further constriction in response to hypocapnia but allowing more vasodilatory reserve during hypercapnia.

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KEY WORDS • carbon dioxide • cerebral blood flow • cerebral infarction • metabolism
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