Reperfusion-Induced Injury to the Blood-Brain Barrier After Middle Cerebral Artery Occlusion in Rats

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Background and Purpose The integrity of the blood-brain barrier may play an important pathophysiological role during postischemic reperfusion. To determine the factors that lead to exacerbation of brain injury by reperfusion, we investigated changes in cerebral blood flow, blood-brain barrier permeability, edema formation, and infarction in permanent or temporary middle cerebral artery occlusion in rats and studied the relation between local cerebral blood flow and blood-brain barrier disruption.

Methods Middle cerebral artery occlusion was performed with the rat suture model, allowing either permanent (6 hours) or temporary occlusion (3 hours of occlusion and 3 hours of reperfusion). We measured brain water, ion contents, and infarct volumes and determined cerebral blood flow using laser Doppler flowmetry and blood-brain barrier permeability with [3H]a-aminoisobutyric acid.

Results During occlusion, cerebral blood flow was reduced to 7% to 15% (permanent) and 10% to 17% (temporary) of the baseline. During 3 hours of reperfusion, it returned to 47% to 80% (lateral cortex) and 78% to 98% (medial cortex) of the baseline. Compared with the contralateral hemisphere, the water content in the ischemic area increased in both permanent and temporary groups (P < .05, P < .01). Both infarct volume and blood-brain barrier disruption were greater in the reperfusion group compared with the permanent occlusion group (P < .05). Blood-brain barrier disruption correlated with cerebral blood flow during reperfusion (P < .05).

Conclusions These findings demonstrate that brain infarct and blood-brain barrier disruption are exacerbated after reperfusion in this model of focal ischemia. Blood-brain barrier disruption may relate to the degree of cerebral blood flow recovery. Thus, although early reperfusion in focal ischemia may preserve penumbra tissue, late reperfusion may increase the tissue injury.

Key Words • blood-brain barrier • brain edema • cerebral blood flow • reperfusion • rats

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were measured with thermocouples (E type, Omega Engineering, Inc.), and brain temperature was regulated with a heating lamp and heating pad to maintain normothermia. Arterial blood pressure was maintained at ≥100 mm Hg by adjustment of the isoflurane concentration. Blood gases were analyzed one time during the experiments to maintain an arterial Pao2 level of ≥100 mm Hg.

MCA occlusion was produced as described previously. Briefly, all branches of the left common carotid artery were isolated and coagulated, including the terminal lingual maxillary artery branches. The internal carotid artery (ICA) was then isolated, and its extracranial branch, the pterygopalatine artery, was ligated close to its origin. A 3-cm length of 3-0 nylon suture with a slightly enlarged and rounded tip was introduced into the intracranial lumen of the external carotid artery and gently advanced into the ICA and circle of Willis to cross the opening of the MCA. For reperfusion, the suture was withdrawn back into the external carotid artery to restore ICA-MCA blood flow.

CBF Measurement

For the CBF measurement, we used an LDF monitor (model BPM2 system, Vasamedics Inc) equipped with a small-caliber probe of 0.7-mm diameter (P-433, Vasamedics). The scalp was incised in the midline and reflected. Flow was measured at three points on the surface of cortex (Fig IA): point A was placed 6 mm lateral and point B 1.5 mm lateral in the ipsilateral ischemic hemisphere; point C was 6.0 mm lateral in the contralateral hemisphere. All three points were 1.0 mm posterior to the bregma. Sampling of brain tissue for the water, ion, and blood-brain barrier permeability determination. Coronal sections 4 mm thick were cut through the middle cerebral artery distribution. The sections were divided into six areas: A, lateral cortex; B, motor cortex; and C, basal ganglia from the ipsilateral and contralateral sides. The tissue samples were processed for water, Na+, K+, and Cl− measurements and PS product determination.

was stereotactically advanced to gently touch the intact dura mater. Wanned 0.9% saline was slowly rinsed around the probe during the experiment to prevent desiccation of the exposed brain. Stable baseline LDF readings were obtained for at least 20 minutes from all three sites of the MCA before occlusion. Continuous digital display of LDF values were averaged over 5-second intervals and recorded every 20 minutes during the MCAO. The CBF values were then calculated and expressed as percentage of the baseline values.

Water, Na+, K+, and Cl− Content

At the end of the experiment, the brains were removed, slices 4 mm thick were taken through the MCA distribution, and the brain tissue was divided into lateral cortex, medial cortex, and basal ganglia regions (Fig IB). These samples were weighted on an electronic analytical balance (Mettler AF100, Mettler Instrument Co) with 0.0001-ng precision to obtain wet weight (W). The tissue was then dried at 95°C for 24 hours and reweighed to obtain dry weight (D). The water content was expressed as percent wet weight, calculated as (W−D)/W×100. The dehydrated section was digested in 1 mL of 1N nitric acid for 1 week. Then a 0.2-mL aliquot was removed and diluted to 2 mL with deionized water and 3 mmol/L CsCl solution, and the Na+ and K+ contents were measured in this solution by atomic emission spectroscopy (IL943 Automatic Flame Photometer, Instrumentation Laboratory Inc). Cl− was measured with a digital chloride monitor (model 442-5000, Haake Buchler Inc).

Morphometric Measurement of Infarct Volume

The area of cerebral infarction was quantified by TTC staining. The brains were removed, and six coronal slices at 2, 4, 6, 8, 10, and 12 mm distal from the frontal pole were dissected with a brain slicer (Activational System Co, Inc). All slices were incubated in 2% TTC (Sigma Chemical Co) solution for 30 minutes at 37°C. Then the slices were fixed in 10% formaldehyde solution. The area of infarction in each section was determined by measuring the area of normally staining brain in the hemispheres ipsilateral and contralateral to the MCAO. The area of infarction was then calculated as (normal volume contralateral minus normal volume ipsilateral). The total volume of infarction was calculated by summing the infarct area in each section and multiplying by the distance between sections.

BBB Permeability and Brain Plasma Volume

The permeability-surface area (PS) product of the BBB to [3H]AIB was determined by a modification of the method of Ohno et al. [3H]AIB (35 μCi) was injected through a femoral vein 10 minutes before the end of the experiment, while [14C]inulin (20 μCi), a plasma volume marker, was given as a second injection 2 minutes before the end of the experiment (both from Du Pont–New England Nuclear). A peristaltic pump withdrew arterial blood continuously throughout the course of the experiment. At the end of the experiment, a terminal plasma sample was taken, and the rat was killed by decapitation. Blood samples were digested in methylobenzethonium hydroxide (Sigma), bleached with H2O2, and counted in an aqueous-based liquid scintillation cocktail. Brain tissue samples were obtained as described in Fig IB, digested in methylobenzethonium hydroxide, and counted in a Beckman 3801 two-channel liquid scintillation counter. The PS product was calculated from the formula

\[ \text{PS} = (C_p - P \times C_f)/J_{C_p \text{dt}} \]

where \( C_p \) is the counts per gram of brain, \( P \) is the plasma volume of the brain determined from the inulin space, \( C_f \) is the terminal plasma concentration of [3H]AIB, and \( J_{C_p \text{dt}} \) is the integral of the [3H]AIB plasma concentration (\( C_p \)) for the experiment. The latter was calculated from the radioisotope content of the continuously withdrawn arterial blood sample. The transfer constant (K) is a function of the effective volume fraction (V) of the blood in which the substance resides, the CBF, the permeability (P) of the substance at the BBB, and the surface area (S) of the BBB.
TABLE 1. Physiological Parameters of Rats During the Experiments

<table>
<thead>
<tr>
<th>Group</th>
<th>MABP, mm Hg</th>
<th>pH</th>
<th>PCO₂, mm Hg</th>
<th>PO₂, mm Hg</th>
<th>Hematocrit, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>pMCAO</td>
<td>101 ±3</td>
<td>7.51 ±0.05</td>
<td>30 ±4</td>
<td>112 ±14</td>
<td>38 ±1</td>
</tr>
<tr>
<td>tMCAO</td>
<td>104 ±8</td>
<td>7.48 ±0.06</td>
<td>31 ±6</td>
<td>112 ±16</td>
<td>39 ±1</td>
</tr>
</tbody>
</table>

MABP indicates mean arterial blood pressure; pMCAO, permanent middle cerebral artery occlusion; and tMCAO, temporary MCAO. Values are mean±SD for 21 rats in each group.

The equation describes the relation between $K$, CBF, $V_f$, and PS product:

$$PS = -CBFxV_fx\ln[1-(K/\text{CBF}xV_f)]$$

When the ratio $K/\text{CBF}xV_f$ is ≤0.2, then $K$ will underestimate the PS product by no more than 10%. The ratio $K/\text{CBF}xV_f$ in our previous studies for AIB was never greater than 2%, indicating $K=PS$.

Statistical Analysis

The data are expressed as the mean±standard deviation of the mean (SD). Statistical differences between the pMCAO and tMCAO groups were evaluated by a two-tailed Student’s $t$ test for unpaired samples. Within a group of animals, results from the left and right hemispheres were compared by a two-tailed Student’s $t$ test for paired samples. $P<.05$ was considered to represent significance.

Results

Cardiovascular and respiratory data from pMCAO and tMCAO are given in Table 1. The values were measured during the occlusion, and they are all in the normal range. The pattern of mean arterial blood pressure during ischemia and in the reperfusion phases is shown in Fig 2. When the suture was inserted or withdrawn, there was usually a slight fall in blood pressure, but it recovered quickly. The brain temperature, based on the temporalis muscle reading, was regulated at 37°C to 37.5°C, and the body temperature averaged 37.5°C during experiments in both pMCAO and tMCAO groups.

Cerebral Blood Flow

Introduction of the suture to block the blood supply to the MCA produced an equal fall in the relative surface blood flow in the lateral and medial cortex areas in the pMCAO and tMCAO groups (Fig 3). Mean percentage of baseline CBF in the contralateral hemisphere was comparable, remaining around 100% in both groups. During the MCAO, the level of CBF was reduced to 7% to 15% (lateral cortex) and 16% to 30% (medial cortex) of the baseline in the pMCAO group. CBF was reduced to 10% to 17% (lateral cortex) and 28% to 40% (medial cortex) of the baseline in the tMCAO group. During the 3 hours of reperfusion, CBF recovered to 47% to 80% (lateral cortex) and 78% to 98% (medial cortex) of the baseline. It should be mentioned that immediately after reperfusion, there was no consistent pattern of hyperemia. Hyperperfusion after 3 hours of MCAO was found in only three rats, in which the blood flow in the ipsilateral hemisphere was >100% of baseline after 1 to 2 hours of reperfusion.
Changes in H₂O and Ion Contents

The changes in water content in the lateral cortex between pMCAO and tMCAO at 6 hours are displayed in Fig 4A. Water in the MCA core territory increased from a value of 79.4±1.3% to 83.5±1.7% in the tMCAO group (P<.001). The increase in the pMCAO group (82.0±1.3%) was less, but statistical analysis showed no significant difference between the two groups (P>.05, Table 2). The water gain of the tissue was accompanied by shifts in Na⁺, K⁺, and Cl⁻. The Na⁺ content increased from 207 to 343 μEq/g dry wt in the tMCAO and from 191 to 292 μEq/g dry wt in the pMCAO group, whereas the K⁺ content decreased from 491 to 359 μEq/g dry wt in the tMCAO and from 464 to 372 μEq/g dry wt in the pMCAO group (Fig 4B and 4C). The changes in Cl⁻ content paralleled changes in Na⁺ content in both groups (Fig 4D). The differences in water and ions between the contralateral and ipsilateral hemispheres for all regions are shown in Table 2. There were no significant differences in ion content between pMCAO and tMCAO groups.

Infarct Volume

The method for inducing focal cerebral ischemia described above yielded reproducible infarction in the MCA territory of the rat’s brain as measured by mitochondrial dehydrogenase staining with TTC. As shown in Fig 5, the infarct volumes were significantly smaller in the pMCAO than in the tMCAO group. In the pMCAO group, the infarct volume was 103±39 mm³, whereas in the tMCAO group, it was 203±38 mm³ (P<.01). When the infarct volumes were divided into cortical and subcortical components, the cortical infarct volumes in the pMCAO group were still smaller than in the tMCAO group (44±23 versus 122±27 mm³, P<.01); however, the subcortical infarct volumes in both groups were not statistically different (57±20 versus 80±14 mm³). The infarct volumes in the subcortical regions were not affected by intervention with reperfusion, which may be because of a poor collateral blood supply in these areas. The ratios of left to right hemispheric areas, which represent swelling, were 1.060±0.006 in the pMCAO and 1.073±0.011 in the tMCAO groups, respectively, and were not significantly different between the two groups.

BBB Permeability

The BBB permeability was measured as the PS products for [¹³H]AIB. Since AIB enters the brain by...
simple diffusion, the PS product for AIB is a measure of the passive permeability. PS products in the contralateral hemispheres were comparable in both pMCAO and tMCAO groups, and they were all in the normal range (Fig 6). In the pMCAO group, a breakdown of the BBB in the ischemic hemisphere was not observed (lateral cortex, 1.25±0.43; medial cortex, 1.58±0.52; and basal ganglia, 1.41±0.39 μL·g⁻¹·min⁻¹, respectively). However, the PS product was significantly increased in the tMCAO group (lateral cortex, 3.69±1.36, P<.001; medial cortex, 2.74±0.71, P<.01; and basal ganglia, 2.60±0.69, P<.01, respectively). These results indicate that the integrity of the BBB was maintained during the first 6 hours of pMCAO but that the BBB is damaged by 3 hours of reperfusion after 3 hours of ischemia.

Correlation Between the Degree of Reperfusion and BBB Disruption

The correlation between the degree of reperfusion and BBB disruption is shown in Fig 7. In the pMCAO group, the final CBF in the lateral cortex was 15±7% of baseline, and the PS product was 1.25±0.43 μL·g⁻¹·min⁻¹. During 3 hours of reperfusion, the pattern of restoration was variable; therefore, the rats were divided into two groups according to the degree of reperfusion. Three rats exhibited hypoperfusion with average CBF in the lateral cortex 35±6% of baseline. Six rats showed good reperfusion, with average CBF in the lateral cortex 93±12% of baseline. The PS product in the poorly reperfused rats was 2.6±0.72 compared with 4.2±1.3 μL·g⁻¹·min⁻¹ in rats with good reperfusion. The BBB disruption was significantly greater in the rats with good reperfusion (P<.05).

Discussion

The postulated mechanisms underlying reperfusion injury are multifactorial and intricately interconnected. They are governed by positive and negative feedback control, cooperativity, and maintenance of homeostatic balance by means of counterpoised antagonists. To study the mechanisms, we developed a suture MCAO model for both permanent and temporary ischemia in the MCA territory without craniotomy. Recirculation is relatively complete because vascular spasm and direct mechanical damage by clips or ligation are avoided. In addition, decompression of intracranial pressure, as occurs with craniotomy, can be avoided. We did not determine whether the ultimate extent of injury was greater after tMCAO compared with pMCAO. It is possible that injury was simply accelerated in tMCAO but that the eventual extent of injury was the same. However, the reason for this study was to develop a model of reperfusion injury.

LDF measurements were used to continuously monitor the changes of local CBF during the MCAO throughout our experiments. The LDF provides instantaneous, nondirectional, continuous, and noninvasive measurements of microcirculatory blood flow in a tissue sample of =1 mm³. Other authors have shown good correlation between LDF and other techniques of monitoring blood flow in the brain microcirculation. Although the results show only relative rates of cortical blood flow, it is essential to verify both occlusion and
reperfusion when studying ischemia-reperfusion. The results demonstrate that failure to establish reperfusion will produce injury. The average CBF in the ischemic lateral cortex of both groups was around 7% to 17% of baseline. The threshold for infarction is similar to that for energy failure/loss of membrane homeostasis. However, the threshold for infarction varies with the duration of the insult. In the rat MCAO model, the ischemic lesion does not improve if reperfusion is delayed beyond the first 90 minutes. The reason is probably a high cerebral metabolic rate and a relatively poor blood supply in rats. During the 3 hours of reperfusion, the blood flow was above the baseline CBF in only a few rats. Thus, there was no reactive hyperemia in most animals in our experiment. Other investigators revealed that in the MCAO model, hyperemia occurs after 1 to 2 hours of occlusion but not after 3 hours of occlusion.

The degree of BBB disruption was measured quantitatively in the present study by determination of the permeability and surface area product for $[^{3}H]$AIB. This indicates that the $[^{3}H]$AIB permeability to serum proteins remains intact for at least several hours after pMCAO. In the tMCAO group, however, the BBB disruption was clearly observed. Since the PS product was two times as great in the pMCAO group as in the tMCAO group, the PS product was still in the normal range. This suggests that the BBB permeability to serum proteins remains intact for at least several hours after pMCAO. In the tMCAO group, however, the BBB disruption was clearly observed. Since the PS product was two times as great in the pMCAO group as in the tMCAO group, the PS product was still in the normal range. However, the degree of BBB disruption was measured quantitatively in the present study by determination of the permeability and surface area product for $[^{3}H]$AIB.

In summary, our experiments, using the rat suture MCAO model, demonstrate that BBB permeability is increased in the rats after tMCAO but not after 6 hours of pMCAO. In addition, the infarct volume in the tMCAO group is greater than in the pMCAO group. Therefore, reperfusion after 3 hours of MCAO may be of little or no benefit in reducing infarct volume and edema and may also cause an earlier BBB disruption.

Acknowledgments

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References


Editorial Comment

A potentially deleterious consequence of reperfusing ischemic tissue is reoxygenation-induced excessive formation of oxygen free radicals.¹² Direct evidence supports the contention that free radicals, including superoxide dismutase and hydroxyl radicals, are formed during reperfusion after cerebral ischemia.³⁴ A number of studies showing the favorable effects of endogenous or exogenous free radical scavenging enzymes also support a pathogenetic role of oxygen free radicals in ischemic brain injury. However, there is little or no evidence in animal studies that has clearly shown that reperfusion after temporary arterial occlusion accentu-
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