Increased Lipid Peroxidation in Vulnerable Brain Regions After Transient Forebrain Ischemia in Rats

Christine Bromont, MS, Christine Marie, PhD, and Jean Bralet, PhD

We examined cerebral lipid peroxidation, estimated by a thiobarbituric acid test, in rat brain regions after 30 minutes of severe forebrain ischemia and at recirculation periods of up to 72 hours. The lipid peroxide levels remained unaltered in all brain regions during ischemia and during the first hour of recirculation but were selectively increased between 8 and 72 hours of recirculation in the ischemia-sensitive regions of the hippocampus, striatum, and cortex. The most pronounced increases (30–37%) were seen at 48 hours of recirculation. In contrast, lipid peroxide levels were unchanged in infarcted brain regions 24 hours after intracarotid injection of microspheres, indicating that reoxygenation of the ischemic brain is a prerequisite for lipid peroxidation. We assessed the lipid peroxidation capacity of cerebral homogenates obtained from rats subjected to ischemia and recirculation by measuring the production of lipid peroxides after aerobic incubation. The homogenates from rats exposed to 30 minutes of ischemia or to 1 hour of recirculation were not more susceptible to peroxidation. However, the production of lipid peroxides was selectively increased in the hippocampus, striatum, and cortex at 8–48 hours of recirculation, suggesting a loss of efficacy of the antioxidant systems. These results, showing a delayed and long-lasting increase in lipid peroxidation that occurs in ischemia-sensitive brain regions and parallels the development of neuronal necrosis, support the hypothesis that free radical processes participate in postischemic neuronal damage. (Stroke 1989;20:918–924)

It has been suggested that cellular damage in cerebral ischemia is at least partly due to oxidative damage, notably that caused by free radical formation and lipid peroxidation. However, definitive proof of its occurrence is still controversial. Several laboratories have provided evidence that lipid peroxidation occurs in vivo either during or after brain ischemia and reperfusion, but other data have failed to support the hypothesis. The controversy derives from the different methods that have been used for the detection and analysis of lipid peroxidation or from the use of different models of brain ischemia.

In our study, we investigated lipid peroxidation using the four-vessel occlusion model of transient ischemia, which produces severe forebrain ischemia and leads to delayed neuronal necrosis in selective brain regions, and a model of cerebral infarction produced by microembolization. Brain ischemia induced by four-vessel occlusion varies in severity according to rat strain. Regional blood flow was therefore measured during and after vascular occlusion to record precisely the ischemic conditions. We assessed the extent of lipid peroxidation by measuring the level of thiobarbituric acid–reactive substances (TBARS) in various cerebral structures at different times after the induction of ischemia. Simultaneously, we investigated the capacity of cerebral lipid peroxidation by measuring the accumulation of TBARS in brain homogenates incubated under aerobic conditions.

Materials and Methods

We performed the study with the four-vessel occlusion model on 98 male Wistar rats (Iffa Credo, France), weighing 250–300 g, that were allowed free access to water and food. Rats were anesthetized with ether, and the vertebral arteries were electrocauterized at the first cervical vertebrae. Four days later, both common carotid arteries were isolated under ether, and arterial clasps were placed around each. Rats were left to recover for approx-
immediately 6 hours before the carotid clamps were tightened to produce four-vessel occlusion. Rats that did not become unresponsive within 60 seconds after clamp tightening were excluded from the study. The carotid clamps were released 30 minutes later, and restoration of carotid artery blood flow was verified visually. One group of rats was used for the measurement of regional blood flow and another group for the measurement of lipid peroxides.

The study with the embolic stroke model was performed on 77 Sprague-Dawley rats (Dépré, France), weighing 250–300 g, which were allowed free access to water and food. Cerebral microembolism was produced by injecting about 4,000 carbonized microspheres (3M, St. Paul, Minnesota, 50-μm diameter, labeled with 85Sr, suspended in 20% polyvinylpyrrolidone) into the left internal carotid artery as previously described.\textsuperscript{15} For measurement of cerebral blood flow, rats were anesthetized with ether and tracheotomized. Polyethylene catheters were inserted in the femoral arteries for continuous blood pressure recording and anaerobic blood sampling. After ether was discontinued, rats were connected to a respirator and anaerobic blood sampling. After ether was discontinued, rats were connected to a respirator and anaerobic blood sampling. After ether was discontinued, rats were connected to a respirator and anaerobic blood sampling.

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We evaluated lipid peroxides by measuring TBARS using a technique modified from Buege and Aust.\textsuperscript{20} This test estimates the level of malondialdehyde (MDA) precursors, including hydroperoxides and endoperoxides.\textsuperscript{21,22} Rats subjected to four-vessel occlusion or embolization were decapitated. The brain was removed and dissected at 0°C. Cerebral structures were homogenized in 10 vol ice-cold 0.05 M phosphate buffer (pH 7) containing 0.015 M Na and 0.145 M K.\textsuperscript{23} The buffer solution had previously been equilibrated with 100% nitrogen for 1 hour before use. To 0.2 ml homogenate were added 1 ml buffer solution and 1.5 ml trichloroacetic (TCA)-thiobarbituric acid (TBA)-HCl reagent prepared in 0.85N HCl with 13.5% wt/vol TCA and 0.33% wt/vol TBA and deoxygenated by bubbling with nitrogen. Samples were then placed in sealed tubes containing nitrogen and were heated for 15 minutes in a boiling water bath. After cooling, 1 ml TCA 70% wt/vol was added, and the precipitate was removed by centrifugation at 2,500g for 10 minutes. The fluorescence of the supernatant was measured on an Aminco-Bowman spectrofluorometer at 553 nm with an excitation wavelength of 515 nm.\textsuperscript{24} The amounts of TBARS were quantified using a standard curve of MDA prepared with malondialdehyde-bis-dimethylacetal (Aldrich-Chimie, France) and expressed as nanomoles MDA per gram wet weight.

Aliquots of brain homogenates were incubated for 1 hour in the phosphate buffer (pH 7) at 37°C in a Dubnoff (Lab-Line Instrs., Inc., Melrose Park, Illinois) metabolic shaker bath under air atmosphere. TBARS were then estimated as previously described and expressed as nanomoles MDA per milligram protein.\textsuperscript{25} Values given as mean±SEM were determined, and the results were analyzed for significance by analysis of variance followed by Dunnett’s t test.

**Results**

Table 1 gives the physiologic parameters of rats subjected to measurement of cerebral blood flow. There were no consistent differences in the parameters between the experimental groups except for an increase in mean arterial blood pressure after 30 minutes of vascular occlusion (158 vs. 128 mm Hg in control rats, p<0.001).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Control</th>
<th>30 minutes of ischemia</th>
<th>Period of posts ischemic reperfusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7.38±0.01</td>
<td>7.37±0.04</td>
<td>7.37±0.02</td>
</tr>
<tr>
<td>Pco₂ (mm Hg)</td>
<td>38±1</td>
<td>33±2</td>
<td>35±2</td>
</tr>
<tr>
<td>PaO₂ (mm Hg)</td>
<td>140±6</td>
<td>131±13</td>
<td>144±3</td>
</tr>
<tr>
<td>Temperature (° C)</td>
<td>37.3±0.1</td>
<td>36.9±0.1</td>
<td>37.1±0.3</td>
</tr>
<tr>
<td>MABP (mm Hg)</td>
<td>128±7</td>
<td>158±8*</td>
<td>113±9</td>
</tr>
</tbody>
</table>

Values are mean±SEM; n, number of rats. MABP, mean arterial blood pressure.

*p<0.001 vs. control group.

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The evolution of regional blood flow after ischemia and recirculation is shown in Table 2. During ischemia, blood flow was reduced to approximately 32% of the control values in the brainstem, to 10%\textsuperscript{14}
TABLE 2. Effect of Four-Vessel Occlusion on Regional Cerebral Blood Flow

<table>
<thead>
<tr>
<th>Structure</th>
<th>Control (n=6)</th>
<th>30 minutes of ischemia (n=6)</th>
<th>1 hour (n=6)</th>
<th>24 hours (n=5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brainstem</td>
<td>128±9</td>
<td>41±7*</td>
<td>93±5*</td>
<td>95±6†</td>
</tr>
<tr>
<td>Hypothalamus</td>
<td>135±8</td>
<td>14±3*</td>
<td>83±14‡</td>
<td>107±13</td>
</tr>
<tr>
<td>Thalamus</td>
<td>163±12</td>
<td>11±2*</td>
<td>78±9*</td>
<td>119±9‡</td>
</tr>
<tr>
<td>Hippocampus</td>
<td>116±4</td>
<td>8±3*</td>
<td>50±8*</td>
<td>72±5‡</td>
</tr>
<tr>
<td>Striatum</td>
<td>144±8</td>
<td>5±1*</td>
<td>46±4*</td>
<td>145±12</td>
</tr>
<tr>
<td>Parietotemporal cortex</td>
<td>165±4</td>
<td>4±1*</td>
<td>49±3*</td>
<td>135±10‡</td>
</tr>
</tbody>
</table>

Values are mean±SEM ml/100 g/min; n, number of rats.

*p<0.001, ‡p<0.01, †p<0.05 vs. control group.

in the hypothalamus, to 7% in the thalamus and hippocampus, and to 3% in the striatum and parietotemporal cortex. After 1 hour of recirculation, a significant hypoperfusion was observed in all brain regions. Flow rates were reduced to approximately 60–70% of control values in the brainstem and hypothalamus, to 45% in the thalamus and hippocampus, and to 30% in the striatum and parietotemporal cortex. At 24 hours of recirculation, blood flow had returned to control values in the striatum but remained reduced (60–80% of control values) in the other brain regions.

The time course of changes in lipid peroxide levels, quantified as nanomoles MDA per gram wet weight, is shown in Figures 1 and 2. Before ischemia, the peroxide levels were similar in all sampled brain regions, with the highest level in the hypothalamus (16.9±0.7 nmol/g) and the lowest in the brainstem (14.6±0.7 nmol/g). In all brain regions, a 30-minute ischemic exposure did not alter significantly the peroxide levels. During recirculation, the pattern of changes differed according to brain region. In the brainstem, hypothalamus, and thalamus (Figure 1), peroxide concentrations did not differ significantly from preischemic values throughout the entire recirculation period. More important changes were found in the hippocampus, striatum, and cortex (Figure 2). After 1 hour of recirculation, the peroxide level was unchanged in the cortex and slightly reduced in the hippocampus (−9%, p=NS) and striatum (−12%, p=NS). These reductions might be related to dilution secondary to the slight increase (about 1%) in brain water content, which was reported in this model during the first hour of recirculation.26 During the 8–72-hour interval, significant increases in peroxide levels occurred in all three regions. The most pronounced change was found after 48 hours of recirculation and reached 30% in the hippocampus (p<0.01), 34% in the parietotemporal cortex (p<0.01), and 37% in the striatum (p<0.01). Afterward, levels declined but remained significantly increased in the cortex (24%) at 72 hours of recirculation.

In our embolic stroke model, intracarotid microsphere injection produces multiple infarcts located ipsilaterally in the striatum, thalamus, hippocampus, and cortex.27 Lipid peroxides were measured 24 hours after embolization in these regions and in the brainstem, which was not affected by the intracarotid injection of microspheres. As shown in Table 3, peroxide levels did not differ significantly between embolized and control rats. The infarcted regions showed a trend toward reduction of peroxide levels (−10 to −15%) that can be explained by...
FIGURE 2. Graph of lipid peroxide levels in hippocampus, striatum, and parietotemporal cortex during ischemia and recirculation. There were 22 rats in control group, six rats subjected to 30 minutes of four-vessel occlusion, and eight, 10, 14, seven and eight subjected to 1, 8, 24, 48, and 72 hours of recirculation after 30 minutes of ischemic exposure, respectively. Values are mean±SEM. (*p<0.05; **p<0.01 vs. control group.)

Discussion

The characteristics of the cerebral ischemia induced by four-vessel occlusion in rats vary according to the rat strain. \(^{13,16,17}\) Changes in regional cerebral blood flow reported in our study are comparable with those described by Pulsinelli et al.\(^ {28}\) Transient four-vessel occlusion in rats produces delayed neuronal necrosis in specific brain regions, the localization and the degree of damage being related to the duration of ischemia. \(^ {14}\) After 30 minutes of ischemia, neuronal damage was found mainly in the hippocampus, striatum, and neocortex, and to a lesser extent, in the thalamus; the brainstem and hypothalamus were not affected.

Our study results show increases in TBARS levels limited to vulnerable brain regions during the postischemic reperfusion period. Changes were not observed during the ischemic period or after 1 hour of recirculation but became manifest between 8 and 72 hours of recirculation. The TBA reaction has frequently been used for measuring lipid peroxidation in biologic samples but has limitations because a part of the TBA-positive material does not originate from lipid peroxides. \(^ {29}\) Nevertheless, change in TBARS level remains a reliable index of lipid peroxidation, especially in comparative studies made on the same biologic material. In brain homogenates incubated under aerobic conditions, Rehncrona et al.\(^ {23}\) have shown that increases in TBARS level were correlated with the loss of polyunsaturated fatty acids.

Postischemic lipid peroxidation has previously been demonstrated during the first hours of recirculation in various experimental models of brain ischemia.\(^ {3,5-8}\) Using the four-vessel occlusion model, MacMillan\(^ {12}\) failed to observe a significant increase in cortical peroxide level for up to 72 hours of recirculation. These data disagree with our findings. The discrepancy might originate from differences in the severity of ischemia or in the nature of the tissue samples. Our study was performed on the parieto-
Temporal cortex, whereas MacMillan\textsuperscript{12} did not specify the location of the cortical region (approximately 75 mg) sampled. It has been shown that the different cortical brain regions were not equally vulnerable after four-vessel occlusion.\textsuperscript{14,30} Neuronal damage appears to be more frequent in the parietal than in the frontal cortex, and the paramedian neocortex is spared from damage.

Oxygen radicals are normally generated during oxidative metabolism but are well controlled by enzymatic and nonenzymatic systems. Thus, an increase in lipid peroxidation can result from either an overproduction of free radicals or from a loss of efficacy of the scavenging systems. Several studies have attempted to measure the evolution of water- or lipid-soluble antioxidant content during or after severe brain ischemia in rats. The total water-soluble antioxidants were found to be significantly reduced in the cerebral cortex between 3 and 24 hours of recirculation after 30 minutes of four-vessel occlusion, whereas values at 2 and 72 hours were unchanged.\textsuperscript{12} While concentrations of both total and reduced ascorbate were unaltered,

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Brainstem</th>
<th>Hypothalamus</th>
<th>Thalamus</th>
<th>Hippocampus</th>
<th>Striatum</th>
<th>Parietotemporal cortex</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control ((n=22))</td>
<td>2.25±0.19</td>
<td>2.60±0.29</td>
<td>2.23±0.13</td>
<td>2.70±0.15</td>
<td>2.52±0.16</td>
<td>3.35±0.15</td>
</tr>
<tr>
<td>30 minutes ischemia ((n=6))</td>
<td>2.07±0.18</td>
<td>2.98±0.54</td>
<td>2.92±0.36</td>
<td>3.09±0.50</td>
<td>2.69±0.28</td>
<td>3.36±0.36</td>
</tr>
<tr>
<td>30 minutes ischemia+1 hour recirc.((n=8))</td>
<td>2.05±0.12</td>
<td>2.78±0.41</td>
<td>2.22±0.15</td>
<td>3.14±0.41</td>
<td>2.39±0.15</td>
<td>3.43±0.32</td>
</tr>
<tr>
<td>30 minutes ischemia+8 hours recirc.((n=10))</td>
<td>2.41±0.35</td>
<td>2.89±0.79</td>
<td>2.54±0.28</td>
<td>3.92±0.67*</td>
<td>3.26±0.32*</td>
<td>4.31±0.34*</td>
</tr>
<tr>
<td>30 minutes ischemia+48 hours recirc.((n=7))</td>
<td>2.19±0.23</td>
<td>3.32±0.79</td>
<td>2.06±0.33</td>
<td>4.20±0.46†</td>
<td>3.23±0.20*</td>
<td>3.79±0.27</td>
</tr>
</tbody>
</table>

Values are mean±SEM; \(n\), number of rats. MDA, malondialdehyde. Cerebral structures were obtained from rats subjected to 30 minutes of four-vessel occlusion and subsequent recirculation. Homogenates were incubated at 37° C for 1 hour, and lipid peroxides were measured.

\(*p<0.05, \dagger p<0.01\) vs. control group.

An overproduction of free radicals may also account for the increased lipid peroxidation seen after reperfusion of the ischemic brain, with several potential sources for the oxygen radicals. Ischemia is accompanied by a marked accumulation of free fatty acids, mainly arachidonic acid, that triggers production of prostaglandins and leukotrienes and generates free radicals.\textsuperscript{36} However, this process is of short duration because of rapid normalization of arachidonic acid level.\textsuperscript{10}

Normally, a major source of oxygen radicals is the electron transport chain located on the inner mitochondrial membrane. Single electrons may leak at the sites of transfer, permitting the reduction of oxygen to superoxide anion. Decrease in the state 3 respiration has been reported to occur in mitochondria from animals exposed to brain ischemia and recirculation.\textsuperscript{37,38} Although the reduction in oxygen uptake rate may result from a variety of mitochondrial perturbations, an overproduction of oxygen radicals may occur if accumulated electrons cannot flow into cytochrome \(a a_3\) despite a resupply of oxygen. Such a mechanism may become critical during the recirculation period as metabolic demand is increased and may lead to a progressive deterioration of mitochondrial function. Brain mitochondria exposed to free radical–generating systems in vitro showed an inhibition of respiratory activity similar to that observed after brain ischemia.\textsuperscript{39} A delayed and progressive impairment of mitochondrial function has been reported in ischemia-sensitive cerebral areas 3–48 hours of recirculation after 30 minutes of four-vessel occlusion.\textsuperscript{38}

Considering the delayed increase in lipid peroxidation that parallels the development of neuronal damage, it cannot be ruled out that the increase represents a late phenomenon in an already irreversibly injured tissue rather than the primary cause of the damage. However, if lipid peroxidation were associated with neuronal necrosis, it would be seen after brain infarction. Our results do not support this hypothesis since lipid peroxide levels were not increased in infarcted brain regions, indicating that reoxygenation of the ischemic brain is a prerequisite for lipid peroxidation.
Regardless of the mechanisms initiating lipid peroxidation after reperfusion of the ischemic brain, the pathogenic importance of peroxidative processes in vivo is not well established. What remains to be determined is whether reduction of postischemic lipid peroxidation by administration of antioxidants or free radical-trapping agents can prevent postischemic brain damage and improve the clinical outcome.

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