Arachidonic Acid Metabolites Contribute to the Irreversible Depolarization Induced by In Vitro Ischemia

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Tanaka, E., S. Niiyama, S. Sato, A. Yamada, and H. Higashi. Arachidonic acid metabolites contribute to the irreversible depolarization induced by in vitro ischemia. J Neurophysiol 90: 3213–3223, 2003. First published August 13, 2003; 10.1152/jn.00542.2003. Intracellular recordings were made from hippocampal CA1 neurons in rat slice preparations. Superfusion with oxygen- and glucose-deprived medium (in vitro ischemia) produced a rapid depolarization ~5 min after the onset of the superfusion. Even when oxygen and glucose were reintroduced immediately after rapid depolarization, the membrane depolarized further (persistent depolarization) and reached 0 mV (irreversible depolarization) after 5 min from the reintroduction. The pretreatment of the slice preparation with a phospholipase A2 (PLA2) inhibitor, para-bromophenacyl bromide, or a cytochrome P-450 inhibitor, 17-octadecynoic acid, significantly restored the membrane to the preexposure potential level after the reintroduction of oxygen and glucose. The administration of 14,15-epoxyeicosatrienoic acid or 20-hydroxyeicosatetraenoic acid did not change the latency of the rapid depolarization and did not allow the membrane potential to recover after the ischemic exposure. In contrast, after pretreatment with cyclooxygenase or lipoxygenase inhibitors, edaravone and a-to-cophanol. These results suggest that the activation of the arachidonic acid cascade via PLA2 and the free radicals produced by arachidonic acid metabolism contribute to the irreversible depolarization produced by in vitro ischemia.

INTRODUCTION

In the mammalian plasma membrane, the sn-2 position of phospholipids is enriched with arachidonic acid (Farooqui et al. 1997; Sapirstein and Bonventre 1997). Lyso phospholipids and arachidonic acid are therefore mainly produced by the hydrolysis of the ester bond at the sn-2 position of glycerophospholipids with phospholipase A2 (PLA2). PLA2 isozymes are classified into four subtypes and type VI PLA2 isozymes are cytosolic. The type VI PLA2 isozymes are further classified into two groups, each Ca2+-dependent or -independent. The initiation of cerebral anoxia or ischemia immediately accumulates free fatty acids including arachidonic acid in the brain in a time-dependent manner (Bazan 1970; Siesjo and Katsura 1992). Arachidonic acid produced by the activation of PLA2 can be metabolized by lipoxygenase (LOX) isozymes, cyclooxygenase (COX) isozymes, and cytochrome P-450 isozymes to leukotrienes, prostaglandins, and other eicosanoids, respectively (Sapirstein and Bonventre 2000). The cytochrome P-450 isozymes are divided into two groups by their functions, α-hydroxylases and epoxygenases (Roman 2002). In the rat brain, α-hydroxyxy enzymes produce mainly 20-hydroxyeicosatetraenoic acid (20-HETE), whereas epoxygenases produce mainly 14,15-epoxyeicosatrienoic acid (14,15-EET) (Alkayed et al. 1996; Amruthesh et al. 1993; Roman 2002). In vivo experiments show the accumulation of leukotrienes and prostanooids in the mammalian brain during and after complete cerebral ischemia (Moskowitz et al. 1984; Stevens and Yaksh 1988). In humans, both the leukotriene C4- and prostaglandin E2-like activity increase in acute cerebral ischemia patients (Aktan et al. 1991). The enzymes that metabolize arachidonic acid also produce oxygen radicals (superoxyl and hydroxyl radicals) (Paller and Jacob 1994; Siesjo and Katsura 1992). Oxygen radicals produce wide-ranging cellular effects, such as lipid peroxidation, inactivation of enzyme, damage to cytoskeleton, and DNA damage (Kontos 2001). It is therefore possible that activation of arachidonic acid metabolism induce severe neuronal damage or death during ischemia and after reperfusion.

Recently, several lines of evidence support the proposal that the activation of PLA2 and the subsequent arachidonic acid metabolites are closely related to the neuronal cell death produced by brain ischemia. Administration of an inhibitor of COX isozymes before exposure to ischemia reduces the area of infarction produced by either occlusion of common carotid arteries or a middle cerebral artery in gerbils or mice (Sasaki et al. 1988). The administration of an inhibitor for LOX isozymes also attenuates the neuronal death produced by occlusion of carotid arteries in gerbils (Rao et al. 1999). In rat hippocampal slice cultures, LOX inhibitors also attenuate the injury caused by oxygen and glucose deprivation (Arai et al. 2001b). Moreover, PLA2 or COX-2 knockout mice show a reduction in the infarcted area produced by occlusion of the middle cerebral artery in comparison with wild-type mice (Bonventre et al. 1997; Iadecola et al. 2001).

In CA1 pyramidal neurons of the rat hippocampal slices, superfusion with oxygen- and glucose-deprived medium (in vitro ischemia) produce a rapid depolarization ~5 min after the onset of the ischemic exposure (Tanaka et al. 1997). When
oxygen and glucose are reintroduced immediately after rapid depolarization, the membrane depolarizes further (persistent depolarization) and reaches 0 mV (irreversible depolarization) after 5 min from the onset of the reintroduction: as a result, the neurons show no functional recovery. The persistent depolarization is a Ca\(^{2+}\)-dependent process that is mediated by the activation of ionotropic glutamate (Glu) receptors and the Ca\(^{2+}\)-induced Ca\(^{2+}\) release from intracellular Ca\(^{2+}\) store sites (Yamamoto et al. 1997). Moreover, blebs appear on the cell body of the CA1 pyramidal neuron 1 min after starting the reintroduction of oxygen and glucose, and the cell body becomes swollen 3 min after (Tanaka et al. 1999). It is therefore possible that during the persistent depolarization, the Ca\(^{2+}\)-dependent PLA\(_2\) may be activated and thereby induce the neuronal damage. Nevertheless, the critical metabolic pathway of arachidonic acid cascade for generating the irreversible depolarization is still unclear.

In the present study, we examined whether or not PLA\(_2\) and the subsequent arachidonic acid metabolites contribute to the generation of the irreversible depolarization induced by in vitro ischemia. Inhibitors for PLA\(_2\) have been administered to the rat hippocampal slices, and the potential changes in CA1 neurons during and after ischemic exposure have been compared between the slices with no administration (control) and the slices administered these drugs. In addition, to clarify the metabolic pathway of arachidonic acid cascade, which leads to the irreversible change, we have examined effects of an inhibitor for LOX, COX, or cytochrome P-450 isozymes on the potential changes after in vitro ischemia.

METHODS

All experiments were conducted in accordance with the Guiding Principles for the Care and Use of Animals in the Field of Physiological Science of the Physiological Society of Japan and had the approval of the Institutional Animal Use and Care Committee in Kurume University. Wistar rats (male, 250–350 g; 8–12 wk old) were rapidly decapitated under ether anesthesia, and the forebrains were rapidly decapitated under ether anesthesia, and the forebrains were completely submerged in the superfusing solution connecting tubing. As a result, the chamber was placed on a nylon net in a recording chamber (volume, 500 μl) and immobilized with a titanium grid placed on the upper surface of the section. The preparation was completely submerged in the superfusing solution (temperature at 36.5 ± 0.5°C, flow rate at 4–6 ml/min).

Intracellular recordings from CA1 pyramidal cells were made with glass micropipettes filled with K acetate (2 M). The electrode resistance was 50–90 MΩ. In conventional intracellular recordings, the apparent input resistance in CA1 neurons was monitored by passing small hyperpolarizing pulses (0.2–0.4 nA, 200 ms) through the recording electrode every 3 s.

Slices were made “ischemic” by superfusion with medium equilibrated with 95% N\(_2\)-5% CO\(_2\) and deprived of glucose, which was replaced with NaCl isosmotically (ischemia-simulating medium). When switching the superfusing media, there was a delay of 15–20 s before the new medium reached the chamber due to the volume of the connecting tubing. As a result, the chamber was filled with the test solution ~30 s after switching the solution. We used one slice for one experiment because the responses to in vitro ischemia could not be reproduced after the first ischemic exposure.

The drugs used were (from Sigma) para-bromophenacyl bromide (para-BPB), arachidonic acid, 17-octadecynoic acid (17-ODA), α-tocopherol, alltopurinol; (from Funakoshi) nordihydroguaiaretic acid (NDGA), 3,4-dihydroxynphenyl ethanol, indomethacin, resveratrol, Dup-697, 20-hydroxyicosatetraenoic acid (20-HETE), 14,15-epoxyeicosatrienoic acid (14,15-EET); and edaravone (gift from Mitsubishi Welpharma). All drugs were dissolved in the perfusate and applied by bath application. The slices were pretreated with media containing test compounds for 20 min before ischemic exposure.

The latency of the rapid depolarization was measured from the onset of superfusion to onset of the rapid depolarization estimated by extrapolating the slope of the rapid depolarization to the slope of the slow depolarization (Tanaka et al. 1997). Recovery after the reintroduction of oxygen and glucose is defined as follows: no recovery, 30–60 min after reintroduction the membrane potential lay between 0 and −19 mV; complete recovery, the membrane potential was more negative than −60 mV; partial recovery, membrane potential repolarized to a value between −20 and −59 mV (Yamamoto et al. 1997).

All quantitative results were expressed as the means ± SD. The number of slices examined is given in parentheses. A one-way ANOVA with the Scheffé post hoc test was used to compare the data. Statistical significance was determined at the level of P < 0.05 otherwise indicated.

RESULTS

Effects of PLA\(_2\) inhibitor on the irreversible depolarization produced by in vitro ischemia

Hippocampal CA1 pyramidal neurons with stable membrane potentials more negative than −60 mV were used for the following studies. The resting membrane potential and the apparent input resistance in CA1 neurons were −70 ± 5 mV (n = 297) and 38 ± 10 MΩ (n = 297), respectively. To elucidate the effects of PLA\(_2\) on the potential change after in vitro ischemia, broad-spectrum inhibitors of PLA\(_2\), para-BPB, and arachidonic acid were administered to the slice preparations. The administration of arachidonic acid at concentrations >100 μM induced a hyperpolarization of a few millivolts, whereas para-BPB (3–100 μM) or arachidonic acid (50–100 μM) did not induce any potential change before ischemic exposure. Figure 1A shows the typical potential changes in CA1 neurons during and after in vitro ischemia in the presence and absence (control) of para-BPB (10 μM) or arachidonic acid (100 μM). In the control condition, in vitro ischemia produced a sequence of potential changes consisting of an initial hyperpolarization, a slow depolarization, and a rapid depolarization (Fig. 1A top). When oxygen and glucose were reintroduced immediately after generating the rapid depolarization, the membrane depolarized further (persistent depolarization) and reached 0 mV. The membrane never showed a restoration to the potential level before exposure to in vitro ischemia (irreversible depolarization). The latency and the maximal slope of the rapid depolarization were 5.2 ± 1.0 min and 9.6 ± 3.7 mV/s (n = 96), respectively. The pretreatment of the slices with para-BPB (100 μM) or arachidonic acid (100 μM) did not significantly change the latency and the maximal slope of rapid depolarization. After the reintroduction of oxygen and glucose, however, both para-BPB and arachidonic acid restored the membrane potential either partially or completely to the preexposure level in a concentration-dependent manner (Fig. 1A and B, and Table 1). The membrane 30 min after the reintroduction significantly repolarized in the presence of para-BPB (10–100 μM) or arachidonic acid (100 μM) in comparison with the absence of the drugs (Fig. 1C and Table
A

FIG. 1. The effects of phospholipase A₂ (PLA₂) inhibitors on the potential changes produced by in vitro ischemia in rat hippocampal CA1 neurons. In vitro ischemia was administered between ↓ and ↑, the preexposure level in this and subsequent figures. A: typical changes in the membrane potential during and after in vitro ischemia in the absence of the drugs (top), and in the presence of para-BPB (middle), or aristolochic acid (bottom). Downward deflections are hyperpolarizing electrotonic potentials elicited by anodal current pulses (in range: 0.2–0.4 nA for 200 ms every 3 s) in this and subsequent figures. The resting potentials were −72, −75, and −73 mV from top to bottom. B: the effects of PLA₂ inhibitors on the percent of neurons exhibiting recovery. □, □, and ◊, no, partial, and complete recovery, respectively. C: the effects of PLA₂ inhibitors on the potential recovery 30 min after the reintroduction of oxygen and glucose. Each column shows the mean ± SD in this and subsequent figures. In the presence of para-BPB or aristolochic acid, the membrane potential repolarized toward the preischemic exposure level in a concentration-dependent manner after the reintroduction of oxygen and glucose. *, P < 0.05; **, P < 0.01; one-way ANOVA with Scheffé post hoc comparisons.

1). It is therefore possible that the arachidonic acid produced by PLA₂ activation thus contributed to the generation of the irreversible depolarization (cf. Fig. 6).

Effects of inhibitors for LOX, COX, and cytochrome P-450 on the irreversible depolarization produced by in vitro ischemia

We next examined effects of enzymes for arachidonic acid metabolism on the irreversible depolarization produced by in vitro ischemia. Solutions containing the cytochrome P-450 inhibitor, 17-ODA, at concentrations >10 μM produced a fine precipitate; we therefore administered 17-ODA at concentrations ≤10 μM. The administration of 17-ODA (1–10 μM) did not change the membrane potential. Figure 2A shows the typical potential changes in CA1 neurons during and after in vitro ischemia in the absence and presence of 17-ODA (10 μM). The pretreatment of the slices with 17-ODA did not significantly change the latency and the maximal slope of rapid depolarization. After the reintroduction, 17-ODA restored the membrane potential either partially (8 of 16 neurons) or completely (2 neurons) to the preexposure level in a concentration-dependent manner (Fig. 2B). The membrane significantly repolarized toward the preexposure level in the presence of 17-ODA (10 μM) 30 min after reintroduction in comparison to the control condition (Fig. 2C, Table 1). On the other hand, LOX or COX inhibitors showed a tendency to restore the membrane potential toward the preexposure level. As shown in Fig. 3A, three of nine neurons showed either a partial or complete recovery in the presence of a broad LOX inhibitor, NDGA (100 μM). Four of nine neurons showed a partial or complete recovery in the presence of a 5- and 12-LOX inhibitor, 3,4-dihydroxyphenyl ethanol (20 μM). Three of 10 neurons showed either a partial or complete recovery in the presence of COX2 inhibitor, Dup-697 (5 μM). Two of 11 neurons showed a partial recovery in the presence of nonselective COX inhibitor, indomethacin (100 μM). One of eight neurons showed a partial recovery in the presence of COX1 inhibitor, resveratrol (100 μM). Two of eight neurons showed a partial recovery in the presence of a xanthine oxidase inhibitor, allopurinol (300 μM). Nevertheless, the membrane potential 30 min after the reintroduction of oxygen and glucose did not show a significant restoration to the preexposure level in the presence of NDGA (100 μM), 3,4-dihydroxyphenyl ethanol (20 μM), Dup-697 (5 μM), indomethacin (100 μM), resveratrol (100 μM), or allopurinol (300 μM; Fig. 3B, Table 1). The pretreatment of the slices with LOX, COX, or xanthine oxidase inhibitors did not significantly change the latency and the maximal slope of rapid depolarization. In addition, the admin-
TABLE 1. Effects of the inhibitors of the arachidonic acid cascade and scavengers of free radicals on the recovery potential after in vitro ischemia

<table>
<thead>
<tr>
<th>Enzyme Blocker</th>
<th>Recovery Potential, mV</th>
</tr>
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<tbody>
<tr>
<td>Control</td>
<td>−3.0 ± 4.4 (96)</td>
</tr>
<tr>
<td>para-BBP</td>
<td></td>
</tr>
<tr>
<td>3 µM</td>
<td>−23.7 ± 31.1 (8)</td>
</tr>
<tr>
<td>10 µM</td>
<td>−44.5 ± 31.8 (14)**</td>
</tr>
<tr>
<td>100 µM</td>
<td>−47.4 ± 22.0 (9)**</td>
</tr>
<tr>
<td>Aristolochic acid</td>
<td></td>
</tr>
<tr>
<td>50 µM</td>
<td>−7.5 ± 9.8 (7)</td>
</tr>
<tr>
<td>100 µM</td>
<td>−27.0 ± 19.3 (16)*</td>
</tr>
<tr>
<td>17-ODA</td>
<td></td>
</tr>
<tr>
<td>1 µM</td>
<td>−11.3 ± 6.9 (9)</td>
</tr>
<tr>
<td>3 µM</td>
<td>−18.8 ± 14.3 (10)</td>
</tr>
<tr>
<td>10 µM</td>
<td>−26.3 ± 24.2 (16)*</td>
</tr>
<tr>
<td>NDGA</td>
<td></td>
</tr>
<tr>
<td>100 µM</td>
<td>−22.5 ± 24.6 (9)</td>
</tr>
<tr>
<td>3,4-Dihydroxyphenyl ethanol</td>
<td></td>
</tr>
<tr>
<td>20 µM</td>
<td>−21.8 ± 27.4 (9)</td>
</tr>
<tr>
<td>Indomethacin</td>
<td>−6.3 ± 13.3 (11)</td>
</tr>
<tr>
<td>Resveratrol</td>
<td></td>
</tr>
<tr>
<td>100 µM</td>
<td>−6.6 ± 12.8 (8)</td>
</tr>
<tr>
<td>Dup-697</td>
<td>−19.7 ± 33.0 (10)</td>
</tr>
<tr>
<td>Allopurinol</td>
<td></td>
</tr>
<tr>
<td>300 µM</td>
<td>−10.1 ± 14.4 (8)</td>
</tr>
<tr>
<td>Edaravone</td>
<td></td>
</tr>
<tr>
<td>100 µM</td>
<td>−14.0 ± 21.0 (7)</td>
</tr>
<tr>
<td>300 µM</td>
<td>−27.6 ± 21.7 (14)*</td>
</tr>
<tr>
<td>α-Tocopherol</td>
<td></td>
</tr>
<tr>
<td>10 µM</td>
<td>−15.1 ± 18.5 (8)</td>
</tr>
<tr>
<td>50 µM</td>
<td>−32.5 ± 26.4 (16)**</td>
</tr>
</tbody>
</table>

Data are presented as means ± SD with values of n shown in parentheses. *P < 0.05. **P < 0.01, one-way ANOVA with Scheffe post hoc comparisons. para-BBP, para-bromophenacyl bromide; PLA₂, phospholipase A₂; 17-ODA, 17-octadecynoic acid; NDGA, nordihydroguaiaretic acid; LOX, lipoxyngeenate; COX, cyclooxygenase.

Effects of eicosanoids on the irreversible depolarization produced by in vitro ischemia

We therefore examined the effects of 14,15-EET and 20-HETE, which are the main products of the activation of cytochrome P-450 isozymes in the rat brain. 14,15-EET or 20-HETE (1 µM) did not produce any potential change. In addition, the pretreatment of the slices with 14,15-EET (1 µM), or 20-HETE (1 µM) did not significantly change the latency of the rapid depolarization: the latency was 5.3 ± 0.2 min (n = 6) and 5.0 ± 0.3 min (n = 6), respectively, in the presence of 14,15-EET and 20-HETE. After the reintroduction of oxygen and glucose, 14,15-EET restored the membrane potential partially toward the preexposure level in only one neuron (Fig. 4A). The membrane did not repolarize at all in the presence of 14,15-EET or 20-HETE 30 min after the reintroduction (Fig. 4B). The membrane potential 30 min after the reintroduction was −4.6 ± 7.4 mV (n = 6) and −5.4 ± 4.8 mV (n = 6), respectively, in the presence of 14,15-EET (1 µM) and 20-HETE (1 µM; Table 1). These results suggest that the arachidonic acid metabolites produced by cytochrome P-450 isozymes do not contribute to the generation of the irreversible depolarization induced by in vitro ischemia.

Effects of free radical scavengers on the irreversible depolarization produced by in vitro ischemia

Cytochrome P-450, LOX, and COX produce oxygen radicals during the arachidonic acid metabolism. To elucidate the effects of oxygen radicals on the irreversible depolarization, free radical scavengers, edaravone and α-tocopherol, were administered. Figure 5A shows the typical potential changes in CA1 neurons during and after in vitro ischemia in the presence and absence of edaravone or α-tocopherol. The pretreatment of the slices with either edaravone (300 µM) or α-tocopherol (50 µM) did not significantly change the latency and the maximal slope of rapid depolarization. After the reintroduction, edaravone and α-tocopherol restored the membrane potential either partially or completely to the preexposure level in a concentration-dependent manner (Fig. 5A and B). The membrane 30 min after the reintroduction was significantly repolarized in the presence of edaravone or α-tocopherol in comparison with the control condition (Fig. 5C, Table 1). From these results, it is concluded that the oxygen radicals generated from arachidonic acid metabolism via cytochrome P-450 isozymes produce the irreversible depolarization following in vitro ischemia (cf. Fig. 6).

DISCUSSION

In rat hippocampal CA1 neurons, PLA₂ inhibitors, para-BBP and aristolochic acid, significantly restored the membrane potential after the in vitro ischemia toward the preexposure level in the majority of neurons tested. A cytochrome P-450 isozyme inhibitor, 17-ODA, also significantly restored the membrane potential in the majority of neurons tested. On the other hand, arachidonic acid metabolites (14,15-EET and 20-HETE) via cytochrome P-450 isozymes did not either accelerate or inhibit the generation of the rapid depolarization and the irreversible depolarization after in vitro ischemia. These results indicate that the reaction mediated by cytochrome P-450 isozymes contributes to the generation of the irreversible depolarization (Fig. 6). The free radical scavengers, α-tocopherol and edaravone, significantly restored the membrane to the preexposure level. This result indicates that the oxygen radicals produced by metabolism of arachidonic acid via cytochrome P-450 isozymes are responsible for the generation of the irreversible depolarization induced by in vitro ischemia.

Effects of PLA₂ inhibitors on the irreversible depolarization after the reintroduction

The present results show that PLA₂ inhibitors, such as para-BBP and aristolochic acid, provide protection against the generation of the irreversible depolarization, and their action is comparable to previous reports that reported that in hippocampal slice culture, para-BBP reduces the propidium iodide uptake after oxygen and glucose deprivation (Arai et al. 2001a). The aristolochic acid partially restored the membrane toward the preexposure level after the reintroduction of oxygen.
and glucose. Because IC50 value of the aristolochic acid for PLA2 activity in human neutrophil is 40 μM (Rosenthal et al. 1989), the concentration (100 μM) used for the hippocampal slices in the present study seems to be reasonable. A previous report showed the intracellular Ca2+ concentration to be markedly elevated at the generation of the rapid depolarization (Tanaka et al. 1997). Both the ionotropic-Glu-receptor-mediated Ca2+ influx and the Ca2+-induced Ca2+ release result in the generation of the persistent depolarization (Yamamoto et al. 1997). Moreover, the cell membrane of the CA1 neuron may be irreversibly damaged during the persistent depolarization because blebs appear on the cell body of the CA1 pyramidal neuron 1 min after starting the reintroduction of oxygen and glucose, and the cell body becomes swollen 3 min after that (Tanaka et al. 1999). Arai et al. (2001a) has also shown that arachidonyl trifluoromethyl keton, a Ca2+-dependent PLA2 inhibitor, reduces neuronal cell death in a hippocampal slice culture after oxygen and glucose deprivation. It is therefore possible that the redistributed arachidonic acid induces the accumulation of Glu in the interstitial space, which may produce a further increase in [Ca2+]i and augment the neuronal damage. In fact, we previously reported that in rat hippocampal CA1 neurons, the ionotropic Glu receptor antagonists, 2-amino-5-phosphonopentanoic acid (AP5) or 6-cyano-7-nitroquinoxaline-2,3-dione (CNQX), restore the membrane to the preischemic exposure level after ischemic exposure (Yamamoto et al. 1997).

FIG. 2. The effects of a cytochrome P-450 isozyme inhibitor, 17-octadecynoic acid (17-ODA), on the potential changes produced by in vitro ischemia in rat hippocampal CA1 neurons. A: typical changes in the membrane potential during and after in vitro ischemia in the absence (top) and presence of 17-ODA (bottom). The resting potentials were –66 (top) and –64 mV (bottom). B: the effects of 17-ODA on the percent of neurons exhibiting recovery. ⊘, ⊙, and □, no, partial, and complete recovery, respectively. C: the effects of 17-ODA on the potential recovery 30 min after the reintroduction of oxygen and glucose. In the presence of 17-ODA, the membrane potential repolarized toward the preischemic exposure level in a concentration-dependent manner after the reintroduction of oxygen and glucose. *, P < 0.05; **, P < 0.01; one-way ANOVA with Scheffé post hoc comparisons.

Effects of cytochrome P-450 isozymes on the irreversible depolarization after the reintroduction of oxygen and glucose

The administration of 14,15-EET or 20-HETE (1 μM) did not alter the membrane potential before the ischemic expo-
sure and the latency of the rapid depolarization during the ischemic exposure, thus suggesting that these products catalyzed by cytochrome P-450 isozymes are not cytotoxic and did not accelerate the generation of the rapid depolarization. On the other hand, a cytochrome P-450 isozyme inhibitor, 17-ODA (10 μM), significantly restored the membrane potential toward the preexposure level. In the brain or liver, the metabolism of various substrates via cytochrome P-450 isozymes leads to the formation of oxygen radicals during the production of metabolites, such as 14,15-EET or 20-HETE (Barth et al. 1998; Mattia et al. 1993; Montoliu et al. 1994; Thompson et al. 2000). These results indicate that the oxygen radicals produced by arachidonic acid metabolism via cytochrome P-450 isozymes contribute to the generation of the irreversible depolarization after in vitro ischemia. Cytochrome P-450 isozymes are found in astrocytes and neurons, including hippocampal pyramidal neurons, in the rat, mouse, and human brains (Bylund et al. 2002; Roman 2002). It is therefore possible that the oxygen radicals produced in both astrocytes and CA1 neurons after in vitro ischemia result in the generation of the irreversible depolarization of the CA1 neurons. The 17-ODA concentration (10 μM) used in this study is comparable with the IC50 for ω-hydroxylation (0.1–7 μM) and epoxidation (0.1–5 μM).

FIG. 3. The effects of lipoxygenase (LOX) inhibitors, cyclooxygenase (COX) inhibitors, and a xanthine oxidase inhibitor on the potential changes produced by in vitro ischemia in rat hippocampal CA1 neurons. A: the effects of LOX inhibitors, COX inhibitors, and a xanthine oxidase inhibitor on the percent of neurons exhibiting recovery. ⊙, ⊙, and ⊙, no, partial, and complete recovery, respectively. Note that the LOX and COX isozyme inhibitor, NDGA, the 5- and 12-LOX inhibitor, 3,4-dihydroxyphenyl ethanol, and the COX-2 inhibitor, DuP-697 restore the membrane completely after the reintroduction of oxygen and glucose in a few neurons tested. B: the effects of LOX inhibitors, COX inhibitors, and a xanthine oxidase inhibitor on the potential recovery 30 min after the reintroduction of oxygen and glucose.

FIG. 4. The effects of the major products of cytochrome P-450 isozymes on the potential changes produced by in vitro ischemia in rat hippocampal CA1 neurons. A: the effects of 20-hydroxyeicosatetraenoic acid (20-HETE), a major product of ω-hydroxylases activity, and 14,15-epoxyeicosatrienoic acid (14,15-EET), a major product of epoxygenases activity, on the percent of neurons exhibiting recovery. ⊙, ⊙, and ⊙, no, partial, and complete recovery, respectively. B: the effects of 20-HETE and 14,15-EET on the potential recovery 30 min after the reintroduction of oxygen and glucose.
via cytochrome P-450 isozymes on the rat renal function (Wang et al. 1998; Zou et al. 1994).

Effects of free radical scavengers on the irreversible depolarization after the reintroduction

There is ample evidence that the arachidonic acid product catalyzed by cytochrome P-450 isozymes leads to the formation of superoxyl radical in the liver and coronal artery (Bondy and Naderi 1994; Fleming et al. 2001; Puntarulo and Cederbaum 1998). Arachidonic acid is also metabolized by COX (and LOX) and thus yields eicosanoids, and a superoxyl radical is thus formed during this process (Kukreja et al. 1986). α-Tocopherol has been shown to be a scavenger of lipoperoxyl radical, superoxide, and hydroxyl radical in many mammalian organs (Burton and Ingold 1986; Fukazawa and Gebicki 1983; Nishikimi et al. 1980; Zalkin and Tappel 1960). The present study showed that the free radical scavengers, α-tocopherol (50 μM) and edaravone (300 μM), restored the membrane after the reintroduction toward the preexposure level in a concentration-dependent manner. In the rat brain homogenate, oxygen radicals produce lipid peroxidation 30 min after incubation at 37°C; the peroxidation is blocked by edaravone with IC₅₀ of 15 μM (Tanaka 2002). It is therefore possible that oxygen radicals, such as superoxyl and hydroxyl radical, mediate the irreversible depolarization after the reintroduction. Our previous report showed that in rat hippocampal CA1 neurons, the inhibitor for nitric oxide (NO) synthase and the NO scavenger restore the membrane toward the preischemic potential level after in vitro ischemia (Onitsuka et al. 1998). Because NO can react with superoxyl radical to yield peroxynitrite, which decomposes and produces a highly toxic free radical, hydroxyl radical, it is possible that NO and oxygen radicals are responsible for the generation of the irreversible depolarization after the reintroduction. It is also possible that the free radicals, including peroxynitrite and hydroxyl radical, may damage the cytoskeleton and/or induce peroxidation of the membrane lipid because large blebs and cell swelling are observed in rat CA1 pyramidal neurons during the persistent depolarization (Tanaka et al. 1999).

Effects of LOX and COX inhibitors on the irreversible depolarization after the reintroduction

In vivo study shows that in all forebrain regions of the gerbil, neurons exhibit dense 5-LOX immunoreactivity and that the transient occlusion of common carotid arteries induces an increase in production of leukotriene C₄, the metabolite from arachidonic acid by 5-LOX, after the reperfusion (Ohitsu et al. 1995). A 5-LOX inhibitor reduces the neuronal death of gerbil hippocampal CA1 region after 6 days from the transient carotid arteries occlusion (Rao et al. 1999). The present results demonstrated that potent LOX isozyme inhibitors, NDGA (100 μM) and 3,4-dihydroxyphenyl ethanol (20
FIG. 6. Putative mechanisms contribute to the generation of the irreversible depolarization induced by in vitro ischemia. In vitro ischemia induces an accumulation of extracellular Glu to activate ionotropic glutamate receptors [N-methyl-D-aspartate (NMDA)- and/or AMPA/kainate-type receptors]. The activation of ionotropic Glu receptors induces a depolarization, which increases permeability of Ca$^{2+}$ at the NMDA-type receptor and voltage-gated Ca$^{2+}$ channels. These mechanisms increase in the intracellular Ca$^{2+}$ concentration ([Ca$^{2+}$]) and trigger the Ca$^{2+}$-induced Ca$^{2+}$ release (CICR) from the intracellular Ca$^{2+}$ store sites (e.g., endoplasmic reticulum). Elevated [Ca$^{2+}$], triggers the activation of PLA$_2$ and nitric oxide (NO) synthase to produce arachidonic acid and NO, respectively. Cytochrome P-450 mainly metabolizes arachidonic acid to produce oxygen radicals. NO reacts with oxygen radicals and yields peroxynitrite (ONOO$^-$). ONOO$^-$ and/or oxygen radicals damage the cytoskeleton and induce peroxidation of the membrane lipid, thus causing the irreversible depolarization. Thin solid arrows: putative routes for intracellular signal transduction systems. Thick solid arrows: putative routs for intracellular signal transduction systems, which mainly contribute to the irreversible depolarization produced by in vitro ischemia. Dashed arrows: putative routes for intracellular signal transduction systems, which contribute relatively little to the generation of the irreversible depolarization.

$\mu$M), showed a complete recovery of the membrane potential after the reintroduction in the minority of neurons tested. In human leukocytes and platelets, the IC$_{50}$ value of NDGA for 5-LOX is 0.2 $\mu$M and that of 3,4-dihydroxyphenyl ethanol for 12-LOX is 4.2 $\mu$M (Kohyama et al. 1997; Salari et al. 1984). NDGA inhibits 12- and 15-LOXs at the high concentration; IC$_{50}$ values for 12- and 15-LOXs are 30 $\mu$M. NDGA also inhibits the COX activity and the IC$_{50}$ is 100 $\mu$M (Salari et al. 1984). The neuroprotective action of NDGA against the ischemic insult in this study may thus result from the inhibition of LOX and COX isozymes. On the other hand, 3,4-dihydroxyphenyl ethanol also inhibits 5-LOX at a high concentration (IC$_{50}$ = 13 $\mu$M) (Kohyama et al. 1997). The neuroprotective effect of 3,4-dihydroxyphenyl ethanol may therefore mainly result from the inhibition of 12-LOX. The present finding seems to be comparable with the previous result in the hippocampal slice culture: the blockade of 12-LOX by baicalein or cinnamyl-3,4-dihydroxy-$\alpha$-cyanocinnamate inhibits the neuronal death induced by oxygen and glucose deprivation for 35 min and a 5-LOX inhibitor, AA861, and thus reduces the neuronal death induced by the 40-min deprivation (Arai et al. 2001b). It is therefore possible that 5- and 12-LOX isozymes contribute to the neuronal death in CA1 region induced by in vitro and in vivo ischemia.

Rat cortical and hippocampal neurons are relatively rich in the COX-2 mRNA and immunoreactivity (Yamagata et al. 1993). The transient occlusion of both common carotid arteries in gerbil and a middle cerebral artery in rat increases in the COX-2 mRNA and immunoreactivity (Miettinen et al. 1997; Ohtsuki et al. 1996). In the present study, DuP-697 (5 $\mu$M), a relatively selective COX-2 inhibitor, restored completely the membrane to preexposure level after the reintroduction in the minority of neurons tested. DuP-697 is $\geq$50-fold more selective for COX-2 than for COX-1: the IC$_{50}$ value for COX-2 is 7 nM and that for COX-1 is 260–500 nM in inflamed kidney (Kargman et al. 1996; Seibert et al. 1996). It is therefore possible that the activation of COX-2 may contribute in some way to the irreversible depolarization induced by in vitro ischemia. On the other hand, potent COX-1 inhibitors, resveratrol (100 $\mu$M) and indomethacin (100 $\mu$M), only partially restored the membrane toward the preexposure level. The ED$_{50}$ value of resveratrol for COX-1 (ability to inhibit the COX-1 activity) is 15 $\mu$M on cancer chemopreventive activity (Jang et al. 1997). The IC$_{50}$ value of indomethacin for COX-1 is 13 $\mu$M, whereas that for COX-2 is >1 $\mu$M on human COXs expressed in COS-1 cells (Laneuville et al. 1994). These previous findings support the idea that the activation of COX-2 rather than COX-1 may be involved in the generation of the irreversible depolarization induced by in vitro ischemia. The present results are comparable to those described in previous reports in which several COX-2 inhibitors where shown to protect the neurons against neuronal death after the transient in vivo ischemia in gerbil or rat (Candelario-Jalil et al. 2002; Govoni et al. 2001; Hara et al. 1998; Nogawa et al. 1997).

In the present study, a xanthine oxidase inhibitor, allopurinol (300 $\mu$M), only partially restored the membrane toward the
for xanthine oxidase is 0.2–0.7 μM on the mouse liver (Elion 1966). Therefore the allopurinol concentration used in this study is high enough to inhibit xanthine oxidase. The contribution of xanthine oxidase to the generation of the irreversible depolarization induced by in vitro ischemia may, if present, be minimal. Based on the findings of all the above-mentioned results, it is likely that the LOX isoforms and the COX-2 may contribute in some extent to the generation of the irreversible depolarization induced by in vitro ischemia (Fig. 6).

Pathophysiological relevance

In our previous reports, changes in the membrane potential produced in CA1 neurons by in vitro ischemia are a mirror image of the DC potential changes produced by in situ ischemia (e.g., cardiac arrest) or asphyxia in the rat brain cortex (Hansen 1978, 1985; Tanaka et al. 1997, 1999; Yamamoto et al. 1997). The rapid depolarization induced by in vitro ischemia corresponds to the terminal depolarization (or phase II depolarization) produced by in situ ischemia or asphyxia. Simultaneous recordings of both intra- and extracellular recordings from rat hippocampal CA1 region have revealed that the rapid depolarization is a mirror image of the DC potential changes produced by in situ ischemia (Brierley and Graham 1984; Brown and Brierley 1966). Therefore the allopurinol concentration used in this study would be a relatively strong ischemic condition in comparison to the four-vessel occlusion model in vivo.

After this strong ischemic condition, the activation of PLA₂ contributes to the generation of the irreversible depolarization. The activation of PLA₂ may produce arachidonic acid, which is oxidized by cytochrome P-450 isozymes. The production of oxygen radicals from arachidonic acid via cytochrome P-450 isozymes may thus contribute to the generation of the irreversible depolarization after reperfusion and in most of the neurons 72 h after (delayed neuronal damage) (Pulsinelli and Brierley 1979; Pulsinelli et al. 1982). Therefore in vitro ischemia in the present study would be a relatively strong ischemic condition in comparison to the four-vessel occlusion model in vivo.

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