NOC/oFQ PKC-dependent superoxide generation contributes to hypoxic-ischemic impairment of NMDA cerebrovasodilation

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Armstead, William M. NOC/oFQ PKC-dependent superoxide generation contributes to hypoxic-ischemic impairment of NMDA cerebrovasodilation. Am J Physiol Heart Circ Physiol 279: H2678–H2684, 2000.—This study determined whether nociceptin/orphanin FQ (NOC/oFQ) generates superoxide anion (O2•−) in a protein kinase C (PKC)-dependent manner and whether such production contributes to hypoxic-ischemic (H-I) impairment of N-Methyl-D-aspartate (NMDA)-induced pial artery dilation in newborn pigs equipped with closed cranial windows. Superoxide dismutase (SOD)-inhibitable nitroblue tetrazolium (NBT) reduction was an index of O2•− generation. Under non-H-I conditions, topical NOC/oFQ (10−10 M, concentration present in cerebrospinal fluid after I or H-I) increased SOD-inhibitable NBT reduction from 1 ± 1 to 20 ± 3 pmol/mm2. PKC inhibitors staurosporine and chelerythrine (10−6 M) blocked NBT reduction (1 ± 1 to 7 ± 2 pmol/mm2 for chelerythrine), whereas the NOC/oFQ receptor antagonist [F/G]NOC/oFQ (1–13)-NH2 (10−6 M) blocked NBT reduction. [F/G]NOC/oFQ(1–13)-NH2 and staurosporine also blunted the NBT reduction observed after I or H-I. NMDA (10−8 M) in cerebrospinal fluid after I or H-I increased SOD-inhibitable NBT reduction from 1 ± 2 to 20 ± 3 pmol/mm2. PKC inhibitors staurosporine and chelerythrine (10−7 M) blunted NBT reduction (1 ± 1 to 7 ± 2 pmol/mm2 for chelerythrine), whereas the NOC/oFQ receptor antagonist [F/G]NOC/oFQ (1–13)-NH2 and staurosporine also blunted the NBT reduction observed after I or H-I. The NOC/oFQ antagonist staurosporine and free radical scavengers partially prevented this impaired dilation (sham: 9 ± 1 and 16 ± 1; H-I: −5 and −10 ± 1; H-I staurosporine pretreated: 3 ± 1 and 6 ± 1%). These data show that NOC/oFQ increased O2•− production in a PKC-dependent manner and contributed to this production after insult and that NOC/oFQ contributed to impaired NMDA-induced pial artery dilation after H-I, suggesting, therefore, that PKC-dependent O2•− generation by NOC/oFQ links NOC/oFQ release to impaired NMDA dilation after H-I. newborn; cerebral circulation; opioids; free radicals; excitatory amino acids; protein kinase C; nociceptin/orphanin FQ; N-methyl-D-aspartate

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studies show that coadministration of NOC/oFQ, in a concentration similar to that in CSF after H-I, diminished NMDA and glutamate-induced pial dilatation under non-H-I conditions (4). Additionally, NOC/oFQ antagonist pretreatment partially restored decremented NMDA and glutamate dilatation after H-I (4). These data then suggest that NOC/oFQ release contributes to impaired excitatory amino acid-induced cerebrovasodilatation after H-I.

The present study, therefore, was designed to determine a potential mechanism whereby NOC/oFQ might contribute to H-I-impaired NMDA cerebrovasodilatation. Importantly, NOC/oFQ has been observed to activate protein kinase C (PKC) (26), and PKC activation has also been observed to generate superoxide anion (O$_2^-$) (2). This study was then designed to determine whether NOC/oFQ generates O$_2^-$ in a PKC-dependent manner and whether such O$_2^-$ production contributes to H-I impairment of NMDA-induced pial artery dilatation.

**METHODS**

Newborn (1–5 days old, 1.3–2.1 kg) pigs of either sex were used in these experiments. All protocols were approved by the Institutional Animal Care and Use Committee. Piglets were initially anesthetized with isoflurane (1–2 minimum alveolar concentration). Anesthesia was maintained with α-chloralose (30–50 mg/kg, supplemented with 5 mg·kg$^{-1}$·h$^{-1}$ iv). A catheter was inserted into a femoral artery to monitor blood pressure and to sample for blood gases and pH. Drugs to maintain anesthesia were administered through a second catheter placed in a femoral vein. The trachea was cannulated, and the animals were mechanically ventilated with room air. A heating pad was used to maintain the animals at 37–39°C.

A cranial window was placed in the parietal skull of these anesthetized animals. This window consisted of three parts: a stainless steel ring, a circular glass coverslip, and three ports consisting of 17-gauge hypodermic needles attached to three precut holes in the stainless steel ring. For placement, the dura was cut and retracted over the cut bone edge. The cranial window was placed in the opening and cemented in the dura was cut and retracted over the cut bone edge. The cranial window was monitored via a sidearm of the cranial window. Blood flow in pial arterioles, viewed with a microscope and video monitor, stopped completely on elevation of intracranial pressure and did not resume until the pressure was lowered (22). To prevent the arterial pressure from rising inordinately (Cushing response), venous blood was withdrawn as necessary to maintain mean arterial pressure no greater than 100 mmHg. As the cerebral ischemic response subsided, the shed blood was returned to the animal. Cerebral ischemia was maintained for 20 min. In combined H+I/R animals, hypoxia (P$_O_2$ = 55 ± 5 mmHg) was produced for 10 min before ischemia by decreasing the inspired F$_O_2$ via a face mask. F$_O_2$ was then maintained at 8% (N$_2$), which was immediately followed by the total ischemia protocol as described above after concomitantly restoring ventilation to room air.

Twenty major types of experiments were performed (all n = 7 animals): 1) generation of O$_2^-$ with NOC/oFQ, 2) generation of O$_2^-$ with NOC/oFQ in the presence of staurosporine, 3) generation of O$_2^-$ with NOC/oFQ in the presence of the NOC/oFQ receptor antagonist [F/G]NOC/oFQ(1–13)-NH$_2$, 4) generation of O$_2^-$ with NOC/oFQ in the presence of chelerythrine, 5) generation of O$_2^-$ with I/R, 6) generation of O$_2^-$ with I/R in staurosporine-pretreated animals, 7) generation of O$_2^-$ with H+/I/R, 8) generation of O$_2^-$ with I/R, 9) generation of O$_2^-$ with H+/I/R in staurosporine-pretreated animals, 10) generation of O$_2^-$ with H+/I/R in [F/G]NOC/oFQ(1–13)-NH$_2$-pretreated animals, 11) generation of O$_2^-$ with H+/I/R in chelerythrine-pretreated animals, 12) vascular responses to agonists in the absence of H+I/R (sham control), 13) vascular responses to agonists after I/R, 14) vascular responses to agonists after I/R in staurosporine-pretreated animals, 15) vascular responses to agonists after I/R in [F/G]NOC/oFQ(1–13)-NH$_2$-pretreated animals, 16) vascular responses after I/R in polyethylene glycol (PEG) superoxide dismutase (SOD) and catalase (CAT)-pretreated animals, 17) vascular responses after H+/I/R, 18) vascular responses after H+/I/R in staurosporine-pretreated animals, 19) vascular responses after H+/I/R in [F/G]NOC/oFQ(1–13)-NH$_2$-pretreated animals, and 20) vascular responses after H+/I/R in SODCAT-pretreated animals.

In the first three series of experiments designed to investigate generation of O$_2^-$, NOC/oFQ (10$^{-10}$ M, Phoenix) was applied to the cerebral cortex for 20 min in either the absence or the presence of staurosporine (10$^{-7}$ M), [F/G]NOC/oFQ(1–13)-NH$_2$ (10$^{-6}$ M, Phoenix) or chelerythrine (10$^{-7}$ M). In the next three series of experiments, generation of O$_2^-$ 1 h after I/R or H+/I/R was investigated in the absence and presence of staurosporine, [F/G]NOC/oFQ(1–13)-NH$_2$, or chelerythrine. In these experiments, staurosporine, [F/G]NOC/oFQ(1–13)-NH$_2$, and chelerythrine were administered 20 min before I/R or H+/I/R. The NOC/oFQ antagonist staurosporine or chelerythrine was kept in constant contact with the cerebral cortex for the duration of the experiment.

In the vascular experiments, responses of arterial vessels to NMDA and glutamate (10$^{-8}$ and 10$^{-6}$ M; Sigma) were obtained before and 1 h after I/R or H+/I/R either in the absence or presence of staurosporine, [F/G]NOC/oFQ(1–13)-NH$_2$, and SODCAT (1,000 and 10,000 U/kg of PEGSOD and CAT, respectively).
O₂ analysis. SOD-inhibitable nitroblue tetrazolium (NBT) reduction was determined as an index of O₂⁻ generation, as previously described (2, 5, 17). Such reduction was determined by placing NBT (2.4 mM, Sigma) dissolved in artificial CSF under one window and NBT (2.5 mM) and SOD (Sigma, 60 U/ml) in artificial CSF under the other window 1 h after I/R or H₁I/R. NBT is water soluble and forms a yellow solution that is converted to nitroblue formazan, an insoluble purple precipitate, in the presence of reducing agents, e.g., O₂⁻. The SOD-inhibitable NBT reduction was determined by the difference in the quantities of nitroblue formazan precipitated on the brain surface under the two windows. Although NBT can be reduced by a variety of agents, SOD provides specificity for the assay. Details of this methodology have been published previously (2, 5, 18).

Statistical analysis. Pial arteriolar diameter, systemic arterial pressure, and NBT reduction values were analyzed using ANOVA for repeated measures or t-test where appropriate. If the value was significant, the data were then analyzed by Fisher’s protected least-significant difference test. An α-level of P < 0.05 was considered significant in all statistical tests. Values are represented as means ± SE of the absolute values or percent changes from control values.

RESULTS

Role of PKC activation in NOC/oFQ-induced O₂⁺ generation during non-H-I and H-I conditions. Topical application of NOC/oFQ (10⁻¹⁰ M, concentration present in cortical periarachnoid CSF after I/R or H₁I/R) to the cerebral cortical surface of non-H-I animals increased SOD-inhibitable NBT reduction (Fig. 1A). This NBT reduction by NOC/oFQ was blunted by staurosporine (10⁻⁷ M) and blocked by the NOC/oFQ receptor antagonist [F/G]NOC/oFQ(1–13)-NH₂ (10⁻⁶ M) (Fig. 1A). NBT reduction by NOC/oFQ was similarly blunted by chelerythrine, another PKC inhibitor (1 ± 1 to 20 ± 3 vs. 1 ± 1 to 7 ± 2 pmol NBT/mm² for absence and presence of chelerythrine, respectively). Under H-I conditions, SOD-inhibitable NBT reduction was increased 1 h after either I/R or H₁I/R (Fig. 1B). This enhanced NBT reduction after either insult was blunted by both staurosporine and [F/G]NOC/oFQ(1–13)-NH₂ (Fig. 1B). NBT reduction after H₁I/R was similarly blunted by chelerythrine (1 ± 1 to 15 ± 2 vs. 1 ± 1 to 6 ± 2 pmol NBT/mm² for the absence and presence of chelerythrine, respectively).

Role of NOC/oFQ, PKC activation, and O₂⁺ generation in impaired excitatory amino acid acid-induced pial artery dilation after I/R and H₁I/R. NMDA and glutamate (both at 10⁻⁸ and 10⁻⁶ M) elicited reproducible pial small artery (120–160 μm) and arteriole (50–70 μm) vasodilation in sham control animals (data not shown). However, NMDA and glutamate-induced vasodilation was attenuated with 1 h of reperfusion after cerebral ischemia (Figs. 2 and 3). This postsult di-
minimized excitatory amino acid dilation was partially prevented by pretreatment with [F/G]NOC/oFQ(1–13)-NH₂, staurosporine, and the free radical scavenger SODCAT (Figs. 2 and 3).

In contrast, NMDA and glutamate-induced vasodilation was reversed to vasoconstriction with reperfusion after H₁I/R (Figs. 4 and 5). This postinsult excitatory amino acid-induced vasoconstriction was attenuated by [F/G]NOC/oFQ(1–13)-NH₂ (Figs. 4 and 5). Both staurosporine and SODCAT administration prevented this postinsult NMDA and glutamate-induced vasoconstriction, although responses were only partially restored to control values (Figs. 4 and 5).

**Effect of staurosporine, chelerythrine, [F/G]NOC/oFQ(1–13)-NH₂, SODCAT, and NOC/oFQ on pial artery diameter.** Staurosporine, chelerythrine, [F/G]NOC/oFQ(1–13)-NH₂, SODCAT, and NOC/oFQ all had no effect on pial artery diameter.

**Blood chemistry.** Blood chemistry and mean arterial blood pressure values were obtained at the beginning and end of all experiments as well as during hypoxia. Hypoxia decreased Po₂ to 35 ± 3 mmHg, whereas the pH, Pco₂, and mean arterial blood pressure values were unchanged. Values for pH, Pco₂, Po₂, and mean arterial blood pressure were 7.45 ± 0.02, 37 ± 3 mmHg, 92 ± 5 mmHg, and 71 ± 5 mmHg, respectively, at the start of experiments vs. 7.44 ± 0.02, 38 ± 3 mmHg, 91 ± 6 mmHg, and 68 ± 6 mmHg, respectively, at the end of experiments. There were no group differences in either blood pressure or blood chemistry values.

**DISCUSSION**

The results of the present study show that, under non-H-I conditions, topical administration of NOC/oFQ, in a concentration approximately that observed in cortical periarachnoid CSF after I/R or H₁I/R (3), results in increased SOD-inhibitable NBT reduction by the newborn pig brain. These data indicate that O₂ was generated. Because staurosporine and chelerythrine blunted this elevation in SOD-inhibitable NBT reduction by NOC/oFQ, these data indicate that PKC activation contributes to O₂ generation by this opioid. Previously, staurosporine was observed to block the NBT reduction after topical application of the PKC activator phorbol 12,13-dibutyrate to the cerebral cortical surface of the piglet, indicating that staurosporine is an efficacious PKC inhibitor (2). Moreover, the putative NOC/oFQ antagonist [F/G]NOC/oFQ(1–13)-NH₂ (1, 16, 17) blocked NOC/oFQ-induced NBT reduction, indicating that this opioid generates O₂ in a selective manner. Additionally, staurosporine, chelerythrine, and [F/G]NOC/oFQ(1–13)-NH₂ blunted I/R and H₁I/R-induced elevated SOD-inhibitable NBT reduction. Previously, I/R was observed to be associated with generation of O₂ on the piglet cerebral cortical surface (5). Results of the present study extend the latter
observation to show that H + I/R also generates O$_2^-$ to a level modestly greater than that observed with I/R alone. New data in this study also suggest that NOC/oFQ contributes to the generation of O$_2^-$ after H-I through activation of PKC. Because the concentration of NOC/oFQ observed in CSF after I/R and H + I/R, 10$^{-10}$ M, did not have any effect on pial artery diameter, such O$_2^-$ generation by NOC/oFQ appears independent of vascular contributory effects. These observations extend those previously published, indicating that activation of cyclooxygenase contributes to O$_2^-$ generation after I/R (5). It should be cautioned, however, that concerns related to the accuracy of the NBT assay have recently been raised (14). For example, many enzymes can cause the reduction of tetrazolium salts to the corresponding formazan. Specifically, the any concentrations of activated oxygen species at cell surfaces, including the endothelium. More importantly, current concepts point toward the significant contribution to damage by the reaction of O$_2^-$ with nitric oxide to form the highly reactive prooxidant peroxynitrite (8, 25). The latter species, and not O$_2^-$, is currently thought to be the more direct mediator of damage. However, because oxygen free radical scavengers did not attenuate impairment of hypercapnic dilation after piglet cerebral I/R (23), postischemic loss of vasodilator responsiveness may not always involve O$_2^-$ or a subsequent reduced form of oxygen.

Because it had been previously observed that NOC/oFQ interacts with NMDA and glutamate in studies unrelated to vascular activity (12, 29, 36), additional studies were designed to investigate the relationship among NOC/oFQ, O$_2^-$, PKC activation, and excitatory amino acid-induced vascular activity after I/R and H + I/R. The results of those studies show that NMDA-induced pial artery dilation was attenuated after I/R, consistent with previous studies (9). After H + I/R, however, dilator responses to NMDA and glutamate were reversed to vasoconstriction. Results of this study extend those of others (9) in that the present study shows that glutamate as well as NMDA-induced pial artery dilation was attenuated after I/R, although responses were only partially reversed the post-H + I/R excitatory amino acid vasodilation. However, both staurosporine and SODCAT administration prevented the post-H + I/R excitatory amino acid vasodilation, although responses were partially restored to control values. Together, these data suggest that PKC-dependent O$_2^-$ generation links NOC/oFQ release to impaired NMDA and glutamate-induced pial artery dilation after H-I. However, because both staurosporine and SODCAT prevented impairment of excitatory amino acid dilation to a greater extent than...
[F/G]NOC/oFQ(1–13)-NH₂ in I/R animals, those data further suggest that other as yet to be determined factors also contribute to activation of PKC, subsequent O₂⁻ generation, and final impairment of excitatory amino acid-induced vasodilation after H+/I/R.

The mechanism by which NMDA-induced pial artery dilation is altered after global cerebral I/R or combined H+/I/R is unclear at this time. Recent work by others suggests a role for oxygen free radicals and protein synthesis (6, 9, 31). In that proposed scenario, increased cyclooxygenase synthesis might account for the previously observed role for oxygen free radicals in I/R-associated cerebrovascular derangement (31). Alternatively, the observed beneficial action of protein synthase inhibitors might relate to the block of the production of an unidentified regulatory protein that is rapidly overexpressed after ischemia (31). Interestingly, adenosine, which is released during hypoxia, has been observed to inhibit NMDA-induced pial artery dilation when coadministered with this excitatory amino acid (7), very similarly to that observed with NOC/oFQ. In those studies it was suggested that adenosine might reduce calcium entry into nerve cells and activation of nitric oxide synthase by promoting hyperpolarization or by blocking N- and Q-type channels (7). It was further suggested that adenosine might reduce presynaptic glutamate release and thus suppress autoamplification of glutamate effects (7). Equally interesting, then, is the observation that NOC/oFQ can inhibit the release of glutamate from rat cerebrocortical slices and can inhibit glutamatergic transmission in the rat spinal cord (12, 29). NOC/oFQ signaling can also be modulated by NMDA (36). More distal mechanisms by which NOC/oFQ-induced O₂⁻ generation might alter NMDA-induced pial artery dilation, as observed in the present study, are currently uncertain.

The experimental design of the present study did not allow for the identification of the cellular site of origin for NOC/oFQ detected in cortical periarachnoid CSF. Potential cellular sites of origin include neurons, glia, vascular smooth muscle, and endothelial cells.

Although glutamate is an excitatory neurotransmitter thought to be a predominant contributor to neurotoxicity associated with H-I (10, 24), little attention has been paid to the functional implications of vascular abnormalities to NMDA and glutamate after such an insult. In the present study, endogenous NOC/oFQ could either function to limit vascular responses to abnormally high glutamate levels after fluid percussion injury or, alternatively, exacerbate them. It is speculated that the latter is more plausible. Recent data show that, at concentrations higher than those studied presently, NOC/oFQ-induced vasodilation is reversed to vasoconstriction after I/R and H+I/R (3). The preadministration of the NOC/oFQ antagonist [F/G]NOC/oFQ(1–13)-NH₂ attenuated reductions in cerebral blood flow observed after H-I, thereby acting in a neuroprotective or vasoprotective manner (3). Therefore, it is hypothesized that the abnormal vascular responses to glutamate and NMDA are deleterious and that H-I-accentuated release of NOC/oFQ contributes to impaired cerebral hemodynamics via modulation of vasodilation by excitatory neurotransmitters.

Opioids are important contributors to the regulation of the piglet cerebral circulation (18). Results of the present study extend such studies by characterizing the contribution of the newly described opioid NOC/oFQ to altered cerebrovascular regulation observed after I/R and H+I/R.

In conclusion, the results of the present study show that NOC/oFQ, in concentrations present in CSF after H-I, increases O₂⁻ production in a PKC-dependent manner and contributes to this production after H-I. These data also show that NOC/oFQ contributes to impaired NMDA and glutamate-induced pial artery dilation after H-I. These data suggest, therefore, that PKC-dependent O₂⁻ generation links NOC/oFQ release to impaired NMDA-induced cerebrovasodilation after H-I.

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REFERENCES


