Effect of Systemic Nitric Oxide Synthase Inhibition on Optic Disc Oxygen Partial Pressure in Normoxia and in Hypercapnia

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PURPOSE. To investigate the effect of systemic nitric oxide synthase (NOS) inhibition on optic disc oxygen partial pressure (PO2) in normoxia and hypercapnia.

METHODS. Intervascular optic disc PO2 was measured in 12 anesthetized minipigs by using oxygen-sensitive microelectrodes placed <50 μm from the optic disc. PO2 was measured continuously during 10 minutes under normoxia, hyperoxia (100% O2), carbogen breathing (95% O2, 5% CO2), and hypercapnia (increased inhaled CO2). Measurements were repeated after intravenous injection of L-NAME (100 mg/kg). Intravenous L-arginine 100 mg/kg was subsequently given to three animals.

RESULTS. Before L-NAME injection, an increase was observed in optic disc PO2 during hypercapnia (ΔPO2 = 5.2 ± 1.7 mm Hg; 18%; P = 0.001) and carbogen breathing (ΔPO2 = 12.8 ± 5.1 mm Hg; 69%; P < 0.001). Optic disc PO2 in normoxia remained stable for 30 minutes after L-NAME injection (4% decrease from baseline; P > 0.1), despite a 21% increase of mean arterial pressure. Optic disc PO2 increased under hypercapnia was blunted after L-NAME injection (ΔPO2 = 0.6 ± 1.1 mm Hg; 3%; P > 0.1), and this effect was reversible by L-arginine. Moreover, L-NAME reduced the response to carbogen by 29% (ΔPO2 = 9.1 ± 4.4 mm Hg; 49%; P = 0.01 versus before L-NAME). The response to hyperoxia was not affected.

CONCLUSIONS. Whereas systemic NOS inhibition did not affect optic disc PO2 in normoxia, a blunting effect was noted on the CO2-induced optic disc PO2 increase. Nitric oxide appears to mediate the hypercapnic optic disc PO2 increase. (Invest Ophthalmol Vis Sci. 2009;50:378–384) DOI:10.1167/iovs.08-2415

Similar to the cerebral arteries and retinal arterioles, the arterioles of the optic nerve head (ONH) are very sensitive to variations of oxygen (O2) and carbon dioxide (CO2) in the blood. Hyperoxia, or high oxygen partial pressure in the arterial blood (PaO2), constricts cerebral arteries1 and retinal arterioles2,3 leading to a decrease of cerebral,1 retinal,4,5 and ONH6,7 blood flow. However, hyperoxia does not alter the tissue oxygen availability, as tissue oxygen partial pressure (PO2) remains relatively stable in the inner retina8,9 and at intervascular areas of the ONH.10,11

On the other hand, hypercapnia, or high carbon dioxide partial pressure in the arterial blood (Paco2), dilates cerebral arteries1,12 and retinal arterioles,13–15 leading to an increase in cerebral,1,12 retinal,13–15 and ONH6,7 blood flow. As a result, inhalation of CO2 increases preretal16 and optic disc Po2.17 In addition, inhalation of carbogen (95% O2, 5% CO2), which increases both PaO2 and Paco2, also increases preretal18,19 inner retinal,20 and optic disc Po2,21 since the vasodilatory effect of elevated Paco2 partially counterbalances the vasoconstriction induced by elevated PaO2. Elevated Paco2 increases tissue Po2 through a dual mechanism: a rightward shift of the oxyhemoglobin dissociation curve,22 which enhances oxygen release from hemoglobin (the Bohr effect), as well as a CO2-induced arteriolar vasodilation.23 Thus, a CO2-induced Po2 increase has been demonstrated at the level of the ONH.17,24

Nitric oxide (NO) has been reported to control CO2-induced vasodilatation in the cerebral25 and the retinal circulation.24 NO is constitutively synthesized from l-arginine by two isoforms of NO synthase (NOS): endothelial NOS, expressed in vascular endothelial cells26 and in some neurons,26 and neuronal NOS, expressed only in neurons.26 In the ONH, NOS activity has been found in vascular endothelial cells27,28 and sparsely in astrocytes29 and the lamina cribrosa.30 NO diffuses rapidly through membranes allowing the signal to spread from cell to cell, with concomitant relaxation of vascular smooth muscle cells.30 Sodium nitroprusside, an NO donor, dilates retinal vessels.30,31 Evidence suggests a role for NO in the control of basal arteriolar tone in the ONH.32 Furthermore, NOS inhibition by l-arginine analogues suppresses CO2-induced vasodilatation in the cerebral23 and the retinal circulation.24 It is not known, however, whether this is also the case at the level of the ONH.

Changes in vessel diameter are technically difficult to demonstrate in the ONH. PO2 measurements, which reflect tissue oxygen availability,16 were performed in this study. PO2 measurements have the advantage of providing information regarding the metabolic status and the needs of the ONH in the normal state and in disease. We conducted this study to investigate the effect of systemic NOS inhibition on optic disc PO2 in normoxia and in hypercapnia.

The data have been published in part in abstract form (Petropoulos IK, et al. IOVS 2005;46:ARVO E-Abstract 3908).

MATERIALS AND METHODS

Experiments were conducted in one eye of 12 minipigs (Arane Animal Facility, Geneva, Switzerland) weighing 10 to 12 kg. The advantage of experimenting on the minipig is the anatomic similarity of its optic nerve to the optic nerve of primates,33 excepting that minipig retinal arteries arise from the ciliary circulation.33 All the experiments were performed in accordance with the ARVO Statement for the Use of Animals in Ophthalmic and Vision Research.
Animal Preparation

Minipigs were prepared for the experiments according to the following protocol: After premedication with intramuscular injection of 2 ml (10 mg) of the tranquilizer midazolam maleate (Dormicum; Roche Pharma, Reinach, Switzerland), 3 ml (120 mg) of the tranquilizer azapenere (Stresnil; Jansen Pharmaceutica, Beerse, Belgium), and 1 ml (0.5 mg) of atropine, anesthesia was induced with 2 to 3 mg of thiopental sodium (Pentothal; Abbott AG, Baar, Switzerland) injected into an ear vein. Analgesia was induced with 2 ml (100 µg) of fentanyl (Sintenyl; Sintetica SA, Mendrisio, Switzerland), and curarization was performed with 2 ml (4 mg) of pancuronium bromide (Pavulon; Organon SA, Pfäffikon, Switzerland). The animals were intubated and artificially ventilated. After arterial, venous, and bladder catheterization, the anesthesia, analgesia, and myorelaxation were maintained throughout the experiment by continuous perfusion of thiopental, fentanyl, and pancuronium, respectively.

Each animal was ventilated at approximately 18 strokes/min, with a continuous flow of 20% O2 and 80% nitrous oxide (N2O) through a variable-volume respirator. Systolic and diastolic arterial blood pressure was monitored through the femoral artery with a transducer. Temperature was maintained between 36°C and 37°C with a thermal blanket.

PaO2, PaCO2, and pH were measured intermittently from the same artery with a blood gas analyzer (Labor-system; Flukiger AG, Menziken, Switzerland) and kept under control by adjusting ventilatory rate, stroke volume, and composition of the inhaled gas.

A head-holder was used to avoid movements from respiration. Upper and lower eyelids were removed as well as a rectangular area of skin surrounding the eye; the bulbar conjunctiva was detached; the sclera was carefully cleaned to 5 mm from the limbus; the superficial scleral vessels were thermocauterized; the globe was fixed with a metal ring sutured around the limbus; and a sclerotomy 2 to 3 mm posterior to the limbus was performed. A small contact lens with a flat exterior surface was placed on the cornea. The pupil was dilated with 1% atropine eye drops, and the fundus was observed with an operating microscope (Carl Zeiss Surgical GmbH, Oberkochen, Germany).

Instruments for PO2 Measurement

Optic disc PO2 measurements were obtained using double-barreled, recess-type, oxygen-sensitive microelecetrodes with a 10-µm tip diameter, as previously described. The microelectrodes were prepared in our laboratory according to a technique described in detail in previous papers. They were calibrated before insertion into the eye and again after withdrawal in a buffered saline solution at 35°C, which was equilibrated with air. The microelectrodes were mounted on an electronic micromanipulator and they were inserted into the vitreous cavity through the sclerotomy. On visualization of the fundus using the operating microscope, the microelectrode tip was positioned at a distance of less than 50 µm from the optic disc, over intervascular areas, as follows: When the microelectrode tip touched the optic disc surface, the reference barrel recorded a sudden negative DC potential shift of several millivolts. At the moment of contact, the position display was zeroed and the microelectrode was then withdrawn less than 50 µm from the optic disc surface. The reference electrode was placed under the skin of the neck.

Experimental Procedure

Each experiment began with baseline continuous optic disc PO2 recordings under systemic normoxia (i.e., breathing of 20% O2 and 80% N2O). When a stable, continuous recording was achieved, systemic hyperoxia was induced by 100% O2 breathing and optic disc PO2 was measured for 10 minutes. At the next step, normoxia was again induced, with the purpose of obtaining a stable optic disc PO2 recording for at least 10 minutes. This recording was considered the baseline before subsequent inhalation of carbogen (95% O2 + 5% CO2) and optic disc PO2 recording over 10 minutes. Normoxia was again induced, a stable optic disc PO2 recording for at least 10 minutes was achieved, and systemic hypercapnia was induced by adding 6% CO2 to the gas mixture and adjusting N2O downward accordingly (i.e., gas mixture: 6% CO2 + 20% O2 + 74% N2O). Optic disc PO2 recording was performed for 10 minutes, and thereafter the animal was allowed to return to normoxia. Each condition was confirmed by corresponding PaO2, PaCO2, and pH measurements. PaO2 had to be high in hyperoxia, PaCO2 had to be high in hypercapnia, and both PaO2 and PaCO2 had to be high during carbogen breathing.

After several cycles of the above-described measurements, we proceeded to intravenous injection of N-nitro-L-arginine methyl ester (L-NAME; Fluka Chemie GmbH, Buchs, Switzerland) 100 mg/kg over 10 minutes. The same experimental procedure was then repeated, and optic disc PO2 measurements were taken under systemic hyperoxia, carbogen breathing, and systemic hypercapnia, as described earlier. In three animals, after optic disc PO2 measurements under different gas conditions before and after L-NAME injection, we proceeded to intravenous injection of L-arginine (Fluka Chemie GmbH) 100 mg/kg over 10 minutes to reverse the action of L-NAME. After this injection, optic disc PO2 measurements were repeated under systemic hypercapnia.

N2O was present in the breathing gas during normoxia, whereas it was adjusted downward whenever CO2 was added to the gas mixture to achieve hypercapnia. It was absent during hyperoxia or carbogen breathing. However, these adjustments are not considered to have affected the results, since we had previously tested the effect of the presence or absence of N2O in the breathing gas during normoxia and had not found any differences in pH, PaCO2, PaO2, or optic disc PO2 (data not shown).

Statistics

Optic disc PO2, PaO2, PaCO2, and pH, as well as their differences from baseline (optic disc ΔPO2, ΔPaO2, ΔPaCO2, and ΔpH), are expressed as the mean ± SD. For each result presented, n represents the number of minipigs studied. In many cases, measurements from different locations on the optic disc of the same eye were obtained. In these cases, the responses from different locations in an individual eye were averaged to a value representing that eye in statistical comparisons.

Values were excluded when PaO2, PaCO2, and/or pH were outside the expected range for the specific gas condition studied in each case. This explains an n < 12 appearing in some results.

Repeated-measures analysis of variance (ANOVA) was used to test the effect of hyperoxia, carbogen breathing, and hypercapnia at four predetermined time points (2, 5, 7, and 10 minutes). Post hoc comparisons at the same time points were performed using paired Student’s t-test with Bonferroni correction for multiple comparisons. Unpaired Student’s t-test with Bonferroni correction was used to compare the response to each gas condition at 7 minutes before and after L-NAME injection. P < 0.05 defined statistically significant differences.

Data were analyzed using commercial software (SPSS, ver. 15.0 for Windows; SPSS, Chicago, IL).

RESULTS

Measurements before Intravenous Injection of L-NAME

Measurements under Systemic Normoxia. Under systemic normoxia (PaO2 = 103.6 ± 17.9 mm Hg; PaCO2 = 35.4 ± 2.4 mm Hg; pH = 7.47 ± 0.04; n = 12), mean optic disc PO2 recorded in intervascular areas of 12 eyes was 18.3 ± 4.0 mm Hg, a level similar to those described previously in minipigs.

Measurements under Systemic Hyperoxia (100% O2). The inhalation of 100% O2 induced a mean increase in optic disc PO2 of ΔPO2 = 3.9 ± 1.6 mm Hg, or 22% (n = 11; Fig. 1) after 7 minutes. Under systemic hyperoxia, mean optic disc PO2 increased from 18.6 ± 4.2 to 22.5 ± 4.9 mm Hg and that difference, although moderate, was statistically significant (Table 1; P < 0.001) but disproportional to a substantial increase
in PaO₂ (ΔPaO₂ = 353.6 ± 83.2 mm Hg, or 365%; ΔPaCO₂ = -2.9 ± 3.6 mm Hg; ΔpH = 0.03 ± 0.03; n = 11), as previously described.²¹

**Measurements during Carbogen Inhalation (95% O₂, 5% CO₂).** The inhalation of carbogen induced a mean increase in optic disc PaO₂ of ΔPaO₂ = 12.8 ± 5.1 mm Hg, or 69% (n = 12; Fig. 1) after 7 minutes, similar to that described previously.²¹ Mean optic disc PaO₂ increased significantly from 17.8 ± 1.9 to 20.9 ± 2.3 mm Hg and that difference, although moderate, was statistically significant (Table 1; P < 0.001) after a significant increase in PaCO₂ (ΔPaCO₂ = -0.03 to 7.38 mm Hg, or 69%; n = 9). The CO₂ increase in the blood reduced pH from 7.47 ± 0.03 to 7.38 ± 0.05 (ΔpH = -0.09 ± 0.03; n = 9).

**Measurements under Systemic Normoxia.** In every case, intravenous injection of L-NAME lasted 10 minutes, and continuous monitoring of arterial blood pressure and optic disc PaO₂ under normoxia was performed for 30 minutes after the onset of injection. In all cases (n = 12), L-NAME injection induced a long-lasting increase in arterial blood pressure. Mean arterial blood

<table>
<thead>
<tr>
<th>Inhaled gas</th>
<th>n</th>
<th>PaO₂</th>
<th>PaCO₂</th>
<th>pH</th>
<th>ΔPO₂ 0–7 min</th>
<th>P 0–7 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hyperoxia</td>
<td>11</td>
<td>450.7 ± 72.4</td>
<td>32.5 ± 3.2</td>
<td>7.49 ± 0.07</td>
<td>3.9 ± 1.6 (22%)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Carbogen</td>
<td>12</td>
<td>467.0 ± 61.5</td>
<td>46.5 ± 2.8</td>
<td>7.39 ± 0.03</td>
<td>12.8 ± 5.1 (69%)</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

**Summary of Optic Disc PO₂ Measurements before and after L-NAME Intravenous Injection in Different Conditions of Gas Inhalation**

**TABLE 1.** Summary of Optic Disc PO₂ Measurements before and after L-NAME Intravenous Injection in Different Conditions of Gas Inhalation

**Before L-NAME**

<table>
<thead>
<tr>
<th>n</th>
<th>0 min</th>
<th>2 min</th>
<th>5 min</th>
<th>7 min</th>
<th>10 min</th>
<th>ANOVA</th>
<th>Post hoc 0–7 min (P)</th>
<th>Mean (SD) ΔPO₂ % 0–7 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hyperoxia</td>
<td>11</td>
<td>18.6 (4.2)</td>
<td>21.5 (4.6)</td>
<td>22.3 (4.6)</td>
<td>22.5 (4.9)</td>
<td>23.2 (5.0)</td>
<td>S &lt;0.001</td>
<td>22 (10)</td>
</tr>
<tr>
<td>Carbogen</td>
<td>12</td>
<td>18.4 (5.1)</td>
<td>25.7 (7.9)</td>
<td>29.9 (9.5)</td>
<td>31.2 (9.9)</td>
<td>33.1 (11.1)</td>
<td>S &lt;0.001</td>
<td>69 (16)</td>
</tr>
<tr>
<td>Hypercapnia</td>
<td>9</td>
<td>17.8 (1.9)</td>
<td>18.8 (1.7)</td>
<td>20.5 (2.4)</td>
<td>20.9 (2.3)</td>
<td>22.6 (1.1)</td>
<td>S 0.001</td>
<td>18 (10)</td>
</tr>
</tbody>
</table>

**After L-NAME**

<table>
<thead>
<tr>
<th>n</th>
<th>0 min</th>
<th>2 min</th>
<th>5 min</th>
<th>7 min</th>
<th>10 min</th>
<th>ANOVA</th>
<th>Post hoc 0–7 min (P)</th>
<th>Mean (SD) ΔPO₂ % 0–7 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hyperoxia</td>
<td>10</td>
<td>18.5 (2.7)</td>
<td>21.1 (3.0)</td>
<td>23.0 (3.6)</td>
<td>23.2 (4.0)</td>
<td>23.7 (4.0)</td>
<td>S 0.001</td>
<td>26 (12)</td>
</tr>
<tr>
<td>Carbogen</td>
<td>12</td>
<td>18.8 (3.0)</td>
<td>23.6 (5.5)</td>
<td>27.0 (5.5)</td>
<td>27.9 (6.6)</td>
<td>29.2 (5.7)</td>
<td>S &lt;0.001</td>
<td>49 (22)</td>
</tr>
<tr>
<td>Hypercapnia</td>
<td>9</td>
<td>19.3 (0.7)</td>
<td>19.5 (1.4)</td>
<td>19.8 (2.0)</td>
<td>19.9 (1.9)</td>
<td>20.0 (2.7)</td>
<td>NS 0.177 (NS)</td>
<td>3 (6)</td>
</tr>
</tbody>
</table>

Data are expressed as the mean ± SD. The results were evaluated by repeated-measures ANOVA followed by post hoc analysis by Bonferroni t-test between baseline (0 min) and 7 min. A statistically nonsignificant PO₂ increase was observed after 7 min of hypercapnia after L-NAME injection. Moreover, comparing the response to CO₂ before and after L-NAME injection, a statistically significant reduction in the response to carbogen and to hypercapnia was noted after L-NAME injection. These results illustrate the blunting effect of NO synthase inhibition on CO₂-induced optic disc PO₂ increase. n, number of minipigs; S, statistically significant difference; NS, statistically non-significant difference.

* P = 0.366 (NS) versus hyperoxia before L-NAME.
† P = 0.01 (S) versus carbogen before L-NAME.
‡ P < 0.001 (S) versus hypercapnia before L-NAME.
became 18.9

\[ \Delta P_{O2} \] did not change significantly at any moment during or after L-NAME injection. The corresponding table shows the mean ± SD of the blood gas levels and of optic disc \( P_{O2} \) variation (\( \Delta P_{O2} \)) 7 minutes after the onset of each condition. \( P \), post hoc comparisons by Bonferroni \( t \)-test between baseline means and means at 7 minutes. Hypercapnia before i-NAM injection induced a significant 18% increase of optic disc \( P_{O2} \), whereas hypercapnia after i-NAM injection did not change optic disc \( P_{O2} \) significantly, due to a blocking effect on \( CO_2 \)-induced \( P_{O2} \) increase induced by i-NAM.

Pressure was 70 ± 17 mm Hg at the onset of injection, increased moderately to 74 ± 21 mm Hg at 5 minutes of injection (5% increase from baseline; \( P > 0.1 \)), became 83 ± 25 mm Hg at 10 minutes of injection (19% increase from baseline; \( P < 0.05 \)), and peaked to 86 ± 26 mm Hg at 30 minutes after the onset of injection (21% increase from baseline; \( P < 0.005 \)). Therefore, mean arterial blood pressure decreased and returned to baseline at 60 to 65 minutes after the onset of injection, without significant variation thereafter.

Optic disc \( P_{O2} \) under normoxia did not change significantly at any moment during or after i-NAM injection (Fig. 3). Optic disc \( P_{O2} \) was 19.2 ± 3.7 mm Hg at the onset of injection, became 18.9 ± 2.8 mm Hg at 5 minutes of injection (2% decrease from baseline; \( P > 0.5 \)), remained at 18.9 ± 3.1 mm Hg at 10 minutes of injection (2% decrease from baseline; \( P > 0.1 \)), and was recorded at 18.5 ± 2.8 mm Hg 30 minutes after the onset of injection (4% decrease from baseline; \( P > 0.1 \)). Levels of \( \text{P}_{\text{aO}_2} \), \( \text{P}_{\text{aCO}_2} \), and pH were within normal ranges during this period.

**Measurements under Systemic Hyperoxia (100% \( O_2 \)).** The inhalation of 100% \( O_2 \) after i-NAM injection induced a mean increase in optic disc \( P_{O2} \) of \( 4.8 ± 2.3 \) mm Hg, or 26% (\( n = 10 \); Fig. 4), after 7 minutes. Under systemic hyperoxia, mean optic disc \( P_{O2} \) increased from 18.5 ± 2.7 to 23.2 ± 4.0 mm Hg and that difference was statistically significant (Table 1; \( P = 0.001 \)) but was again disproportional to a substantial increase in \( \text{P}_{\text{aO}_2} \) (\( \Delta \text{P}_{\text{aO}_2} = 376.2 ± 64.7 \) mm Hg, or 361%; \( \Delta \text{P}_{\text{aCO}_2} = -4.0 ± 4.0 \) mm Hg; \( \Delta \text{pH} = 0.03 ± 0.03; n = 10 \)). The response to hyperoxia after i-NAM injection was not significantly different from the response to hyperoxia before i-NAM injection (Table 1; \( P = 0.366 \)).

**Measurements during Carboxen Inhalation (95% \( O_2 \), 5% \( CO_2 \)).** The inhalation of carboxen after i-NAM injection induced a mean increase in optic disc \( P_{O2} \) of \( 9.1 ± 4.4 \) mm Hg, or 49% (\( n = 12 \); Fig. 4), after 7 minutes. Mean optic disc \( P_{O2} \) increased significantly from 18.8 ± 3.0 to 27.9 ± 6.6 mm Hg (Table 1; \( P < 0.001 \)). Under the effect of carboxen, both \( \text{P}_{\text{aO}_2} \) and \( \text{P}_{\text{aCO}_2} \) increased significantly (\( \Delta \text{P}_{\text{aO}_2} = 392.3 ± 71.3 \) mm Hg, or 376%; \( \Delta \text{P}_{\text{aCO}_2} = 11.8 ± 3.2 \) mm Hg, or 35%; \( n = 12 \)). The \( CO_2 \) increase in the blood reduced pH from 7.46 ± 0.05 to 7.37 ± 0.05 (\( \Delta \text{pH} = -0.08 ± 0.02; n = 12 \)). However, the response to carboxen after i-NAM injection was significantly lower than the response to carboxen before i-NAM injection (Table 1; \( P = 0.01 \)), as i-NAM reduced the response to carboxen by 29% on average.

**Measurements under Systemic Hypercapnia.** The increase in \( CO_2 \) in the inhaled gas after i-NAM injection induced a mean increase in optic disc \( P_{O2} \) of \( 9.1 ± 4.4 \) mm Hg, or only 3% (\( n = 9 \); Fig. 2), after 7 minutes. Under systemic hypercapnia, mean optic disc \( P_{O2} \) increased from 19.3 ± 0.7 to 19.9 ± 1.9 mm Hg, but that difference was not statistically significant (Table 1; \( P = 0.177 \)) despite a significant increase in \( \text{P}_{\text{aCO}_2} \) (\( \Delta \text{P}_{\text{aCO}_2} = -6.4 ± 3.7 \) mm Hg, or 6%; \( \Delta \text{P}_{\text{aO}_2} = 15.8 ± 5.4 \) mm Hg, or 44%; \( n = 9 \)). The \( CO_2 \) increase in the blood reduced pH from 7.44 ± 0.06 to 7.35 ± 0.05 (\( \Delta \text{pH} = -0.09 ± 0.04; n = 9 \)). In addition, the response to hypercapnia after

![Figure 2. Continuous typical recordings of optic disc \( P_{O2} \) during hypercapnia before (left) and after (right) i-NAM injection. The corresponding table shows the mean ± SD of the blood gas levels and of optic disc \( P_{O2} \) variation (\( \Delta P_{O2} \)) 7 minutes after the onset of each condition. \( P \), post hoc comparisons by Bonferroni \( t \)-test between baseline means and means at 7 minutes. Hypercapnia before i-NAM injection induced a significant 18% increase of optic disc \( P_{O2} \), whereas hypercapnia after i-NAM injection did not change optic disc \( P_{O2} \) significantly, due to a blocking effect on \( CO_2 \)-induced \( P_{O2} \) increase induced by i-NAM.](https://iovs.arvojournals.org/pdfaccess.ashx?url=/data/journals/iovs/932956/)

![Figure 3. Continuous typical recordings of optic disc \( P_{O2} \) during 30 minutes of normoxia after intravenous injection of i-NAM. Optic disc \( P_{O2} \) did not change significantly at any moment during or after i-NAM injection, despite a progressive increase of mean arterial blood pressure (MAP), which showed a peak 21% increase on average 30 minutes after the onset of i-NAM injection. A brief decrease in optic disc \( P_{O2} \) lasting less than 1 minute was recorded at the very beginning of each i-NAM injection, apparently caused by a transient decrease in MAP due to the shock of the bolus injection.](https://iovs.arvojournals.org/pdfaccess.ashx?url=/data/journals/iovs/932956/)
l-NAME injection was significantly lower than the response to hypercapnia before l-NAME injection (Table 1; \( P < 0.001 \)).

In three minipigs that received l-NAME, after \( P_{\text{O}_2} \) measurements performed according to the protocol, intravenous injection of l-arginine was administered. In all three minipigs, l-arginine reversed the effect of l-NAME on the increase in optic disc \( P_{\text{O}_2} \) under hypercapnia, since the observed pattern of optic disc \( P_{\text{O}_2} \) variation under hypercapnia after l-arginine injection was identical with that observed under hypercapnia before l-NAME injection (data not shown).

**DISCUSSION**

In the present study, systemic NOS inhibition with intravenous injection of l-NAME was shown not to affect baseline optic disc \( P_{\text{O}_2} \) in normoxia, but to be capable of attenuating the response to hypercapnia and to carbogen breathing. These results indicate a blunting effect of systemic NOS inhibition on \( CO_2 \)-induced optic disc \( P_{\text{O}_2} \) increase, demonstrating NO as a mediator of \( CO_2 \)-induced \( P_{\text{O}_2} \) increase at the level of the ONH.

Baseline measurements before l-NAME injection confirmed the existence of a \( CO_2 \)-induced \( P_{\text{O}_2} \) increase at the level of the ONH, as previously shown.21 Systemic hypercapnia induced a marked increase in \( P_{\text{O}_2} \) but only a moderate, yet statistically significant, increase in optic disc \( P_{\text{O}_2} \), which was then regulated to stable levels. This was apparently the result of arteriolar vasoconstriction at the level of the ONH, a mechanism that prevents excessive ONH \( P_{\text{O}_2} \) increase. In contrast, carbogen breathing induced a marked increase of both \( P_{\text{O}_2} \) and \( P_{\text{CO}_2} \), as well as a marked increase in optic disc \( P_{\text{O}_2} \) due to the Bohr effect and because, most probably, the vasodilatory effect of elevated \( P_{\text{CO}_2} \) partially counterbalanced the vasoconstriction due to elevated \( P_{\text{O}_2} \). Furthermore, systemic hypercapnia induced a marked increase in \( P_{\text{CO}_2} \) and a linear, moderate but statistically significant increase in optic disc \( P_{\text{O}_2} \) due to the Bohr effect and because of the vasodilatory effect of elevated \( P_{\text{CO}_2} \).

Injection of l-NAME blunted the \( CO_2 \)-induced increase in optic disc \( P_{\text{O}_2} \). A nonsignificant 3% increase in optic disc \( P_{\text{O}_2} \) in response to hypercapnia after l-NAME injection versus a significant 18% increase in response to hypercapnia before l-NAME injection was noted. This effect was reversible when l-arginine, an NO donor, was injected, confirming that the lack of NO was responsible for the blunting effect of l-NAME on the \( CO_2 \)-induced increase in optic disc \( P_{\text{O}_2} \). Moreover, a 49% increase in optic disc \( P_{\text{O}_2} \) in response to carbogen after l-NAME injection versus a 69% increase in response to carbogen before l-NAME injection was observed, despite comparable \( P_{\text{CO}_2} \) levels between these two conditions. l-NAME reduced the response to carbogen by 29% on average. These observations showed that the presence of NO is necessary to enable the maximum \( CO_2 \)-induced increase in optic disc \( P_{\text{O}_2} \), indicating NO as a mediator of that increase.

The blunting effect of l-NAME on the response to \( CO_2 \) noted in the present study is in accordance with the results of previous animal studies in neural tissue showing a hypercapnia-induced increase in NO concentration in the brain22 as well as a reduction through NOS inhibition of \( CO_2 \)-induced retinal vasodilation24 and of \( CO_2 \)-induced retinal24 and cerebral38,39 blood flow increase. In addition, Schmetterer et al.40 showed a blunting effect of NOS inhibition on \( CO_2 \)-induced increase in blood velocities in the middle cerebral artery and the ophthalmic artery in humans, an effect reversed by l-arginine. Thus, regarding neural tissue oxygen availability, there is growing evidence of an important role of NO in the response to hypercapnia. According to Iadecola and Zhang,41 NO may act as a permissive factor in hypercapnia by facilitating the action of other vasodilators. Further studies are needed to confirm this assumption at the level of the ONH.

Optic disc \( P_{\text{O}_2} \) under normoxia did not change significantly during or after l-NAME injection, even though MAP increased by 21% from baseline. This is in accordance with the study of Bouzas et al.11 in minipigs: intervascular ONH \( P_{\text{O}_2} \) 200 \( \mu \)m deep in the tissue remained stable during and after intravenous injection of nitro-arginine, even though arterial blood pressure increased by 28%. Moreover, in the inner retina of minipigs, Donati et al.42 found no effect of intravenous injection of nitro-arginine on arteriolar diameter, whereas local juxta-arteriolar application of the same NOS inhibitor induced transient vasoconstriction, suggesting a role of NO of neuronal origin from the glial cells surrounding the retinal arterioles in maintaining the basal retinal arteriolar tone. Studies exploring the effect of systemic NOS inhibition on ONH blood flow are somewhat conflicting: A decrease in ONH blood flow assessed
by different methods was reported in rabbits\textsuperscript{35,44} and in humans,\textsuperscript{32} whereas Buerk et al.\textsuperscript{45} report variable changes of baseline ONH blood flow after NOS inhibition in cats, suggesting that other autoregulatory mechanisms compensated for the effects of NOS inhibition in the cat ONH. Thus, NO may not control basal arteriolar tone in the ONH, or other autoregulatory mechanisms may intervene to keep ONH pO\textsubscript{2} stable during NOS inhibition. These potential mechanisms may be insufficient in the presence of hypercapnia.

The molecular relation between CO\textsubscript{2} and the 1-arginine-NO pathway in the retinal and ONH circulation is quite challenging but is still open to research. It is generally believed that after an increase in Paco\textsubscript{2}, CO\textsubscript{2} diffuses readily into the interstitial space and the cytoplasm of peripial arteriolar cells and/or arteriolar endothelial cells where, at the catalyzing effect of carbonic anhydrase, the production of H\textsuperscript{+} lowers the interstitial and intracellular pH.\textsuperscript{46} This probably acts as a stimulus to increase the cytosolic free Ca\textsuperscript{2+}, part of which is bound to calmodulin, which in turn activates NOS to produce NO from 1-arginine.\textsuperscript{26} Donati et al.\textsuperscript{42} have presented evidence that Müller cells may be a source of NO, since these cells have a significant rate of arginine biosynthesis. NO activates guanylyl cyclase to increase the concentration of cGMP in the vascular smooth muscle cells\textsuperscript{36-47} and in capillary pericytes.\textsuperscript{48} This lowers the intracellular Ca\textsuperscript{2+} concentration by activating Ca\textsuperscript{2+}-sensitive K\textsuperscript{+} channels and inhibiting the release of Ca\textsuperscript{2+} from the sarcoplasmic reticulum, thus inducing relaxation of the vascular smooth muscle cells of the arteriolar wall.\textsuperscript{47}

In a previous study, prostaglandins have also been shown to mediate a CO\textsubscript{2}-induced pO\textsubscript{2} increase at the level of the ONH.\textsuperscript{17} The 1-arginine-NO pathway and the prostaglandin pathway may act in parallel, synergistically, or they may interact. Evidence of this interaction exists in the literature. NO can activate cyclooxygenase (COX),\textsuperscript{48} and it can also react with superoxide to form peroxynitrite with subsequent lipid peroxidation and liberation of arachidonic acid.\textsuperscript{49} Moreover, NOS/COX cross talk has been described wherein NO activates COX-1 but inhibits COX-2-derived prostaglandin production.\textsuperscript{50} Conversely, prolonged hypercapnia can increase retinal blood flow in piglets by PGE\textsubscript{2}-mediated increased expression of eNOS mRNA.\textsuperscript{51} Further research is needed to demonstrate similar mechanisms at the level of the ONH.

The role of the 1-arginine-NO pathway in the CO\textsubscript{2}-induced pO\textsubscript{2} increase at the level of the ONH raises clinical interest in the presence of glaucomatous and/or ischemic ONH disease. A relative vasconstriction has been shown at the level of the ONH in patients with glaucoma that can be partially reversed by hypercapnia.\textsuperscript{52} However, a possible increase in NOS activity due to hypercapnia at the level of the ONH may expose the ONH to excessive levels of NO, which in turn could be destructive to the retinal ganglion cells through the formation of peroxynitrite, which may trigger apoptosis.\textsuperscript{53} This adverse event should be taken into account if CO\textsubscript{2} is to be used for the treatment of glaucoma. In addition, polymorphism of the endothelial NOS gene has been proposed as an important risk factor in the development of nonarteritic anterior ischemic neuropathy.\textsuperscript{54} Potential use of CO\textsubscript{2} to increase oxygen availability may not be effective in these patients.

In conclusion, the results of the present study showed that systemic NOS inhibition with 1-NAME in minipigs does not reduce optic disc pO\textsubscript{2} in normoxia but exerts a blunting effect on CO\textsubscript{2}-induced optic disc pO\textsubscript{2} increase. Evidence is thus given that the 1-arginine-NO pathway mediates the increase in pO\textsubscript{2} due to hypercapnia at the level of the ONH, as this reaction is believed to happen in the inner retina and in the brain. Since prostaglandins are also mediators of the increase, studies are needed to elucidate the NO-prostaglandin interaction in neural tissue.

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