The effect of oxygen on dynamic cerebral autoregulation: critical role of hypocapnia

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1Department of Biomedical Engineering, Toyo University, Saitama; and 2Morinomiya University of Medical Sciences, Osaka, Japan; 3Department of Human Kinetics, Faculty of Health and Social Development, University of British Columbia Okanagan, Kelowna, Canada; and 4Department of Cardiovascular Dynamics, National Cardiovascular Center Research Institute, Osaka, Japan

Submitted 30 October 2009; accepted in final form 27 December 2009

Ogoh S, Nakahara H, Ainslie PN, Miyamoto T. The effect of oxygen on dynamic cerebral autoregulation: critical role of hypocapnia. J Appl Physiol 108: 538–543, 2010. First published January 7, 2010; doi:10.1152/japplphysiol.01235.2009.—Hypoxia is known to impair cerebral autoregulation (CA). Previous studies indicate that CA is profoundly affected by cerebrovascular tone, which is largely determined by the partial pressure of arterial O2 and CO2. However, hypocapnia also attenuates dynamic CA (CAd), while hypocapnia causes vessel constriction, a decrease in CBF, and improves CAd (1). Hypoxia (10, 12, 35) and hypoxia (15) also influence both the cerebral and the systemic circulation. Acute hypoxia enhances muscle sympathetic discharge, cardiac output, skeletal muscle blood flow, and heart rate (HR), with little or no alteration in arterial blood pressure (ABP) (14). In the brain, isocapnic hypoxia causes cerebral artery dilation mediated by local metabolite production (e.g., adenosine) (36).

There have been a number of studies examining the influence of hypobaric and normoxic hypoxia on CA. Studies have suggested that there is CA impairment in both newcomers to high altitude (3, 18, 21) and in permanent high-altitude residents living above 4,000 m (19), particularly in the presence of acute mountain sickness (7, 34). During isocapnic hypoxia, studies have suggested that CA is either maintained (2) or impaired (17, 31). Differences in findings may be related to varying degrees of hypoxia (14 vs. 12 vs. 10%) and, importantly, the degree of subsequent hypocapnia. Because hypocapnia improves CAd (1) and is a result of increased hypoxic ventilatory drive via the peripheral chemoreflex, it is difficult to separate the adverse effects of hypoxia per se on CA from the enhancing effects of hypocapnia. Therefore, the purpose of the present study was to examine the influence of hypoxia with and without consequent hypocapnia on both middle cerebral artery blood velocity (MCA V) and CAd. Moreover, while the effects of hypoxia on CA have been partially explored (5, 17, 31), the effects of hyperoxia without concomitant changes in PaCO2 are unknown. Although PaCO2 has a marked effect on cerebral vascular tone, which defines CAad (1, 24), this response is also influenced by arterial PO2 (PaO2). Therefore, investigation of the effect of hypoxia on CAad will also provide relevant clues regarding the mechanisms by which O2 may affect dynamic CBF regulation. To address these questions, we compared MCA V and CAd during isocapnic hypoxia, hypocapnic hypoxia, and isocapnic hypoxia to identify the interactions between hypoxia and concomitant influence of hypocapnia on dynamic CBF regulation.

METHODS

Nine healthy, nonathletic men, age 22.7 ± 5.8 yr (mean ± SD), were recruited to participate in the study, as approved by the Human Subjects Committee of Morinomiya University of Medical Sciences (no. 004). Subjects were free of any known cardiovascular and pulmonary disorders and were not using prescribed or over-the-counter medications. Before the experiment, each subject gave informed, written consent and visited the laboratory for familiarization with the techniques and procedures. Subjects were requested to abstain from caffeinated beverages for 12 h and strenuous physical activity and alcohol for at least 24 h before the day of the experiment.
All studies were performed at a room temperature between 23 and 24°C with external stimuli minimized. HR was monitored using a lead II electrocardiogram. ABP was monitored with tonometry (BP-608 Evolution II, Omron-Column, Tokyo, Japan). This system utilizes an state-of-the-art multisensor array technology to detect pulse waves at the radial artery. The APB system was calibrated from obtained arterial pulse waves by the auscultatory method before each condition. The MCA V was obtained by transcranial Doppler ultrasonography (TCD) (WAKI, Atys Medical, St. Genislaval, France). A 2-MHz Doppler probe was placed over the temporal window and fixed with an adjustable headband and adhesive ultrasonic gel (Tensive, Parker Laboratories, Orange, NJ). Arterial oxygen saturation (SaO2) was assessed at the ear using pulse oximetry (9900-MKII, Kohken Medical, Tokyo, Japan). Ventilatory responses were measured using an open-circuit apparatus. The subjects breathed through a face mask attached to a low-resistance one-way valve with a flowmeter. The valve mechanism allowed subjects to inspire room air or a selected gas mixture from a 200-liter Douglas bag containing 14% O2, 21% O2, or 40% O2 in 0% CO2 with nitrogen (N2) balance. The total instrumental dead space was 200 ml. Respiratory and metabolic data during the experiments were recorded by an automatic breath-by-breath respiratory gas analyzing system, consisting of a differential pressure transducer, sampling tube, filter, suction pump, and mass spectrometer (ARCO2000-MET, Arcosystem, Chiba, Japan). We digitized expired flow, CO2 and O2 concentrations, and derived tidal volume, minute ventilation, end-tidal PO2 (PETO2), and end-tidal Pco2 (PETCO2). Flow signals were computed to single-breath data and matched to gas concentrations identified as single breaths using the peak PETCO2, after accounting for the time delay in gas concentration measurements. The corresponding O2 uptake and CO2 output values were calculated by N2 correction. During each protocol, HR, ABP, MAP, MCA Vmean, and CVCi were defined by calculating their means during the 4 s immediately before thigh-cuff release. Following the baseline at each condition, the thigh cuffs were inflated to more than the systolic pressure (220 mmHg) for 3 min. After the 3 min of cuff inflation, the cuffs were deflated, and measurements were continued 2 min postdeflation to assess the CBF response to a rapid and transient drop in ABP to identify CAo. Previous investigations have indicated that, under resting conditions, the cuff occlusion-induced ischemia does not induce a muscle metaboreflex activation (29). All conditions were randomized and separated by a minimum of 20 min.

**Data Analysis**

Beat-to-beat mean arterial pressure (MAP) and mean MCA V (MCA Vmean) were obtained from each waveform. The cerebrovascular conductance index (CVCi) was calculated by dividing MCA Vmean by MAP and was used as an estimate of changes in cerebrovascular conductance. The derived CVCi during acute hypotension is not directly related to steady-state cerebrovascular conductance, because changes in the vascular compliance affect CBF (1). Control values of MAP, MCA Vmean, and CVCi were defined by calculating their means during the 4 s immediately before cuff-release. Changes in MAP, MCA Vmean, and CVCi during cuff release were determined relative to their concomitant control values. At time 1.0–3.5 s from cuff release, the rate of change in CVCi is directly related to CAo (1). The rate of regulation (RoR) is calculated as an index of CAo (1).

$$RoR = (\Delta CVCi/\Delta T)/\Delta MAP$$

where $\Delta$CVCi/$\Delta$T is the slope of the linear regression between CVCi and time (T); and $\Delta$MAP was calculated by subtracting control MAP from MAP averaged during the interval from 1.0 to 3.5 s (1).

**Statistics**

Statistical comparison of variables and RoR were made utilizing a repeated-measures one-way analysis of variance. A Student-Newman-Keuls test was employed post hoc when interactions were significant. Statistical significance was set at $P < 0.05$, and results are presented as means ± SE. Analyses were conducted using SigmaStat (Jandel Scientific Software, SPSS, Chicago, IL).

**Table 1. Steady-state cerebrovascular and cardiorespiratory variables during normoxia, hyperoxia, isocapnic hypoxia, and hypocapnic hypoxia**

<table>
<thead>
<tr>
<th></th>
<th>Intervention 1: Normoxia</th>
<th>Intervention 2: Hyperoxia</th>
<th>Intervention 3: Hypoxia</th>
<th>Intervention 4: Hypocapnic Hypoxia</th>
<th>$P$</th>
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</thead>
<tbody>
<tr>
<td>HR, beats/min</td>
<td>65 ± 3</td>
<td>58 ± 8</td>
<td>68 ± 6</td>
<td>69 ± 3</td>
<td>0.347</td>
</tr>
<tr>
<td>MAP, mmHg</td>
<td>85 ± 3</td>
<td>91 ± 4</td>
<td>85 ± 2</td>
<td>88 ± 5</td>
<td>0.243</td>
</tr>
<tr>
<td>MCA Vmean, cm/s</td>
<td>65 ± 3</td>
<td>62 ± 4</td>
<td>68 ± 4*</td>
<td>54 ± 4*†</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>PETO2, %</td>
<td>20.7 ± 0.1</td>
<td>40.8 ± 0.1*</td>
<td>13.6 ± 0.1*†</td>
<td>13.6 ± 0.1*†</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>PETCO2, Torr</td>
<td>104 ± 1</td>
<td>245 ± 2*</td>
<td>58 ± 1*‡</td>
<td>67 ± 2*†</td>
<td>&lt;0.001</td>
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<tr>
<td>N2O, Torr</td>
<td>37 ± 1</td>
<td>36 ± 1</td>
<td>37 ± 1</td>
<td>29 ± 1*‡</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>SaO2, %</td>
<td>97.7 ± 1.3</td>
<td>99.6 ± 0.9*</td>
<td>88.9 ± 1.7*†</td>
<td>94.2 ± 2.3*†</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>VE, l/min</td>
<td>8.8 ± 0.6</td>
<td>9.5 ± 0.5</td>
<td>9.6 ± 0.5</td>
<td>13.1 ± 0.6*†</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>VT, ml</td>
<td>647 ± 22</td>
<td>694 ± 41</td>
<td>692 ± 46</td>
<td>843 ± 34*†</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>RR, breaths/min</td>
<td>13.7 ± 0.8</td>
<td>13.9 ± 0.8</td>
<td>14.0 ± 0.8</td>
<td>15.6 ± 0.7*‡</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Values are means ± SE. HR, heart rate; MAP, mean arterial pressure; MCA Vmean, middle cerebral artery mean blood velocity; FiO2, fraction of inspired oxygen (O2); PETO2, end-tidal PO2; PETCO2, end-tidal Pco2; VE, minute ventilation; VT, tidal volume; RR, respiratory rate. *$P < 0.05$, different from normoxia; †$P < 0.05$, different from hyperoxia; ‡$P < 0.05$, different from isocapnic hypoxia.
RESULTS

Hyperoxia, Hypoxia, and Hypocapnic Hypoxia

During the four experimental conditions, PETO2 and PETCO2 were accurately controlled by the selected mix of inspired gases and control of respiratory pattern (Table 1). During the control intervention (intervention 1; 21% O2), PETO2 and PETCO2 were 104 ± 1 and 37 ± 1 Torr, respectively. In intervention 2 (40% O2), PETO2 was elevated to 245 ± 2 Torr (P < 0.001), whereas PETCO2 was well maintained at preintervention level (36 ± 1 Torr). Likewise, while hypoxia (intervention 3) decreased PETO2 to 58 ± 1 Torr (P < 0.001 vs. baseline), PETCO2 was maintained by voluntary control of respiration in the hypoxic (37 ± 1 Torr) condition. During intervention 4 (14% O2 with hyperventilation), voluntary hyperventilation decreased PETCO2 from 37 ± 1 to 29 ± 1 Torr. Compared with control, SaO2 was reduced during both isocapnic and hypocapnic hypoxia; however, the reduction in SaO2 was greater during the isocapnic hypoxic condition compared with the hypocapnic hypoxia condition (Table 1). During all interventions (interventions 2–4), there were no alterations in HR (P = 0.347) and MAP (P = 0.243). However, the isocapnic hypoxic intervention tended to increase MCA Vmean (4%; P = 0.237). In contrast, controlled hyperventilation during hypoxia decreased MCA Vmean (19%; P < 0.001). The CVCi increased at hypoxia and decreased at hypocapnic hypoxia condition (see Fig. 2).

Thigh Cuff Release During the Experimental Conditions

The release of the thigh cuffs elicited an acute decrease in ABP at all conditions. Changes in MAP with thigh deflation were −27 ± 3% (normoxia; intervention 1), −30 ± 2% (isocapnic hypoxia; 2), −28 ± 2% (isocapnic hypoxia; 3), and −27 ± 4% (hypocapnic hypoxia conditions; 4). There were no differences in the changes in MAP with each condition. As intended, these decreases in ABP were sufficient to evoke a transient decrease in MCA Vmean (1). As a reflection of CAd, changes in MCA Vmean were smaller (average 23%) from baseline compared with MAP in all conditions, particularly during the hypocapnic hypoxia condition (18 ± 3%, P < 0.001).

The RoR, an index of CAd, was calculated from the change in CVCi from 1 to 3.5 s (Fig. 1). Compared with normoxia, RoR was not altered with isocapnic hypoxia (0.321 ± 0.028/s; Fig. 2). Isocapnic hypoxia significantly attenuated RoR (0.202 ± 0.003/s; 27%, P = 0.043). In contrast, hypocapnic hypoxia increased RoR (0.444 ± 0.069/s) from normoxia (0.311 ± 0.054/s; +55%, P = 0.041).

DISCUSSION

The primary finding of the present study is that isocapnic hypoxia impairs CAd; however, mild hypocapnia counteracts this to improve CAd during hypoxia. These data indicate that, at least acutely, the respiratory chemoreflex may compensate for hypoxic-induced impaired in CAd through hyperventilation and consequent hypocapnia. That hypocapnia affected CAd even under conditions of hypoxia reinforces the idea that CBF control is influenced to a greater extent by PaCO2 than by PaO2.

Hypocapnia leads to cerebral vasoconstriction, which attenuates the further fall of brain tissue PCO2, while hypercapnia causes cerebral vasodilation, limiting elevations in brain tissue PCO2. Changes in blood-gas concentrations modified dynamic CBF regulation (1, 24). For example, there was a significant inverse relationship between CAd and PaCO2, indicating that the response rate of CAd is due to cerebral vascular tone as determined by levels of PCO2 (1). However, while hypoxia is a cerebral vasodilator, reflected in a rise in CBF in proportion to the severity of isocapnic hypoxia (6, 11), under normal conditions the hypoxia-induced activation of peripheral chemoreceptor activity leads to hyperventilatory-induced lowering of PaCO2 and subsequent cerebral vasoconstriction. Thus the cerebrovascular bed receives conflicting signals during exposure to acute hypoxia, which coincides with hypoxic ventilatory response and resultant hypocapnia (4). An important physio-

Fig. 1. Normalized data of continuous recording of mean arterial pressure (MAP), middle cerebral artery mean blood velocity (MCA Vmean), and cerebrovascular conductance index (CVCi) during deflating thigh occlusion cuffs during normoxia (A), isocapnic hypoxia (B), and hypocapnic hypoxia (C). The thigh occlusion cuffs were deflated at time 0. Data are shown in units relative to control pre-deflating values obtained during −4 to 0 s. Bold lines through CVCi data from 1 to 3.5 s after cuffs deflating were determined by linear regression analysis to identify rate of regulation (RoR) as an index of dynamic cerebral autoregulation. Slope, slope of the regression line between relative CVCi and time from 1 to 3.5 s; avg. MAP, averaged (1–3.5 s) relative change in MAP from baseline.
hyperventilation and subsequent reduction in arterial P CO2 

Torr), assessed using the transfer function analysis approach. In this study, some impairment (e.g., change 

low-frequency gain) in CAd was evident at 17% O2. In con-

Fig. 2. Top: steady-state CVCi. Bottom: RoR as an index of dynamic cerebral 

autoregulation for each subject (line plots) and averaged values (bars) during 

normoxia, hypocapnia, isocapnic hypoxia, and hypocapnic hypoxia. HV, hyperven-
tilation. Values are means ± SE. *P < 0.05, different from normoxia; $P < 0.05, 
different from hyperoxia; #P < 0.05, different from isocapnic hypoxia.

logical point of the present study was, therefore, to examine the 

response of CBF regulation to isocapnic hypoxia without the 

influence of the subsequent chemoreflex changes in PETCO2.

Comparison with Previous Studies

There are three previous studies to compare our findings. 

First, Iwasaki et al. (17) found that 5 min of mild hypoxia 

[inspired O2 fraction (FiO2) = 0.15; inspired PO2 ~105 Torr] 

impaired CAa, as assessed by using the transfer function analysis 

approach. In this study, some impairment (e.g., change in 

power spectrum density and tendency for increases in 

low-frequency gain) in CAa was evident at 17% O2. In con-

trast, Ainslie et al. (5) reported no changes in CAa under more 

severe hypoxia (FiO2 = 0.12 and 0.10, inspired PO2 ~85 and 70 

Torr), assessed using the transfer function analysis approach. 

In contrast, another study (31) reported that CAa was impaired 

during acute (5 min) exposure to hypoxia (FiO2 = 0.12). 

Unfortunately, none of these studies separates the effects of 
isocapnic vs. poikiloicapnic hypoxia; that the cerebral vascula-
ture is highly sensitive to CO2 limits interpretation of these 

studies with respect to the independent effects of hypoxia. In 

view of the current findings, differences in the degree of 

hypoxia and variability in the chemoreflex response and sub-

sequent degree of hypocapnia may explain these inconsistent 

results. Our findings underscore the critical role of arterial 

hypocapnia influencing the effects of acute hypoxia on CAa.

Hyperoxia

Hyperoxia (>60 s) is a respiratory stimulant (8), causing 
hyperventilation and subsequent reduction in arterial PCO2 
(approximately −3–5 Torr), accompanying vasconstriction in 
the arterioles and thereby reducing CBF (5, 12). Another novel 
finding from the present study unchanged CAa under condi-
tions of hyperoxia. There is a possible threshold for the 
modification of PO2 on CAa, i.e., from hyperoxia to hypoxia, 
CAa may be modified exponentially. We prevented the normal 
hypoxia-induced hyperventilation and subsequent hypocap-
nia. Based on the findings of the hypocapnic-hypoxa interven-
tion, the possibility that hyperoxic-induced hypocapnia may 
act to improve CAa would seem likely.

The Mechanisms of Action

The mechanism of changes in CAa seems to be associated 
with cerebral vascular tone. Reductions in cerebral vascular 
tone via sympathetic nerve activity blockade (25, 37) or hy-
percapnia (1) impaired CAa. In the present study, hypoxia 
caused decreased cerebrovascular tone (an increase in CVCi; 
Fig. 2), accompanied by cerebral vasodilation. In contrast, high 
cerebrovascular tone, induced via hypercapnia (1), improved 
CAa. We found that CAa was improved by hyperventilation, 
even during hypoxia, which causes further cerebral vasocon-
striction. Thus cerebral vascular tone may modify CAa. How-
ever, heavy exercise (26), hypertensive patients (16), and 
orthostatic stress (38) impaired CAa, despite a high cerebral 
vascular tone.

Implications

High altitude. There have been a number of studies that have 
examined the influence of high altitude on CA. Studies indicate 

an impairment in CA (3, 18, 21) in both newcomers to high 
alitude and in permanent high-altitude residents living above 

4,000 m (19), especially in the presence of acute mountain 
sickness (7, 34). These studies reported impairment in CAa, 

despite the presence of marked hypocapnia, which is in con-
strained with those from the present study, where CAa was 
improved with the addition of hypocapnia. Differences in the 

experimental protocol (i.e., length of hypoxic exposure), se-
verity, and type of hypoxic exposure (i.e., simulated vs. high 
alitude) may underpin these different findings. Nevertheless, 

the possibility that those with a more vigorous hypoxic venti-
latory responses at high altitude (and, therefore, greater degree 
of hypocapnia) may benefit from a better maintained CAa and, 
therefore, protection against acute mountain sickness (7, 34) 
warrants further study.

Pathology. Arterial hypoxemia is a common consequence of 
chronic lung and cardiac diseases. Little is known with respect 
to how CAa and CBF may be regulated in these disorders (4). 
However, transient drops in Pao2 are known to occur in a 
range of physiological (e.g., postural change, exercise) and 
pathophysiological (e.g., asthma, sleep apnea, congestive heart 
failure, anxiety attacks) situations. The possibility that such 
hypocapnia is of teleological relevance to offset hypoxic-
induced impairment in CAa warrants further research.

Methodological considerations. A potential limitation of 
estimating MCA V using TCD is that changes in the diameter of the insonated vessels could modulate MCA V independently of 
flow. Numerous studies support the validity of MCA V as an 
index of regional CBF (9, 23, 27, 30, 32, 33). Moreover, 
studies have shown that MCA diameter is relatively unchanged 
in the range of 23–60 Torr for PaCO2 (13, 30, 32). However, 
evidence of unchanged MCA diameter during hypoxia is still 
less clear. Nevertheless, it is noteworthy that the observed 
MCA V response during isocapnic hypoxia was comparable to
findings by Noth et al. (22), who have previously assessed the CBF response to isocapnic hypoxia using MRI (22). Consistent with this report, earlier studies (28) have used the Doppler power signal as an index of the cross-sectional area of the MCA diameter and have also reported that the diameter is unchanged during comparable hypoxia conditions. Collectively, these findings support the use of MCA V as a valid measure of CBF. In addition, TCD-determined blood flow velocity in large basal cerebral arteries (i.e., MCA) is widely used as an index of CBF and can identify a transient change in CBF (24).

A consequence of the hypoxic hypocapnia condition was that the hyperventilation caused a small rise in \( \text{PETO}_2 \) (≈9 Torr) and, therefore, \( \text{SaO}_2 \). Nevertheless, alterations in \( \text{CA}_4 \) occur at 15% \( \text{O}_2 \); some changes were also evident at 17% \( \text{O}_2 \) (17). Moreover, because of the alveolar-to-arterial \( \text{PO}_2 \) gradient [normally = <5–8 Torr (5, 20)], \( \text{PaO}_2 \) would likely be <50 Torr. Thus it would seem unlikely that the small increase in \( \text{PETO}_2 \) and, therefore, vasodilatory stimulus would alter our findings.

In summary, isocapnic hypoxia impairs \( \text{CA}_4 \), whereas it is unchanged under conditions of isocapnic hyperoxia. In addition, hyperventilation-induced mild hypocapnia acts to improve \( \text{CA}_4 \), even during hypoxic conditions. It seems likely that, at least acutely, respiratory chemoreflex may compensate for hypoxia-induced impairment in \( \text{CA}_4 \).

Acknowledgments

The authors appreciate the time and effort expended by the volunteer subjects.

Grants

This study was supported in part by a Grant-in-Aid for Scientific Research (no. 19500574) from the Japanese Ministry of Education, Culture, Sports, Science and Technology; a Grant from the Descente and Ishimoto Memorial Foundation for the Promotion of Sports Science; and a Grant from the Kozukai Foundation for sports and education.

Disclosures

No conflicts of interest are declared by the author(s).

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