Cardiovascular and Cerebrovascular Responses to Acute Isocapnic and Poikilocapnic Hypoxia in Humans

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ABSTRACT

We examined the cardiovascular and cerebrovascular responses to acute isocapnic (IH) and poikilocapnic (PH) hypoxia in ten male subjects (25.7 ± 4.2 yrs, mean ± SD). Heart rate (HR) mean arterial pressure (MAP) and middle cerebral artery blood flow velocity (\(\overline{V} p\)) were measured continuously during two randomized protocols of 20 min of step IH and PH (45 Torr). HR was elevated during both IH (p<0.01) and PH (p<0.01), with no differences observed between conditions. MAP was modestly elevated across all time points during IH, but only became elevated after 5 min during PH. During IH, \(\overline{V} p\) was elevated from baseline throughout the exposure with a consistent hypoxic sensitivity of \(\sim 0.34 \text{ cm}\cdot\text{s}^{-1}\cdot\%^{-1}\) desaturation (p<0.05). The \(\overline{V} p\) response to PH was biphasic with an initial decrease from baseline occurring at 79 ± 23 sec, followed by a subsequent elevation, becoming equivalent to the IH response by 10 min. The nadir of the PH response exhibited a hypoxic sensitivity of \(-0.24 \text{ cm}\cdot\text{s}^{-1}\cdot\%^{-1}\) desaturation. When expressed in relation to end-tidal PCO\(_2\), a sensitivity of \(-1.08 \text{ cm}\cdot\text{s}^{-1}\cdot\text{Torr}^{-1}\) was calculated, similar to previously reported sensitivities to euoxic hypocapnia. Cerebrovascular resistance (CVR) was not changed during IH. During PH, an initial increase in CVR was observed. However, CVR returned to baseline by 20 min of PH. These data show the cerebrovascular response to PH consists of an early hypocapnia-mediated response, followed by a secondary increase, mediated predominantly by hypoxia.

KEYWORDS

Cerebral blood flow, blood pressure, heart rate, hypoxia, hypocapnia
INTRODUCTION

There is substantial interaction between the cardiovascular and respiratory systems to ensure adequate oxygen delivery to organs and tissues. On a systemic scale, the oxygen transport cascade can be affected critically by alterations in respiration and or convective transport via the circulation. However, in the face of such perturbations, \( O_2 \) transport is optimized by cardiorespiratory reflex interactions and adaptations. For instance, inputs from cardiovascular (e.g. baroreceptors) and respiratory (e.g. chemoreceptors) sensors share common neural pathways, inputting into common areas within the brainstem (9). Further, these afferent inputs have been shown to interact, modulating the differential control of both systems (18, 44). In addition, regulation of blood flow in the brain impacts importantly on tissue pH affecting central chemoreception and in turn respiration (51). Equally, changes in respiration can affect \( \text{PaCO}_2 \) and in turn cerebral blood flow (CBF).

The hypoxia of altitude, concomitant with a systemic alkalosis, places a unique stress on the cardiorespiratory system. At the onset of exposure a rise in cardiac output is observed that is driven by increases in heart rate. With longer exposure (days to weeks), cardiac output then falls in conjunction with stroke volume while heart rate (HR) remains elevated (6, 10, 29, 50). Under these conditions, inadequate adaptations may result in exercise fatigue or worse, deteriorate into life threatening conditions such as acute mountain sickness, pulmonary or cerebral edema. Further, in other pathological situations where respiratory and or cardiovascular function is compromised (e.g., sleep apnea or pulmonary hypertension) secondary ailments may also evolve due to
cardiorespiratory linkages. Thus, an understanding of cardiorespiratory interactions is important from basic and applied physiology, and clinical perspectives.

Previous investigations of the cardiovascular responses to acute hypoxia have typically focused on discreet “steady state” time points many minutes into a hypoxic exposure. Additionally, experiments designed to investigate the cardiovascular response to specific carotid body stimulation have generally been carried out with isocapnia, thereby avoiding the concomitant hypocapnia that is typically associated with hypoxia at altitude. Since carbon dioxide is a known, potent regulator of blood flow (37), the influence of changes in arterial PCO$_2$ need to be accounted for when studying the effects of hypoxia where concomitant hypocapnia may influence the local vasculature, the chemical regulation of cardiovascular responses and integrated cardiorespiratory control.

The early work of Shapiro et al. attempted to address the influence of eucapnic versus isocapnic hypoxia on CBF in humans (43). This work elegantly illustrated a blunting of CBF due to alkalosis in the face of ongoing hypoxia. However, technical limitations precluded a comprehensive comparison between similar levels of hypoxia, nor was an investigation of other cardiovascular factors carried out. In a previous investigation from our laboratory, the cardiovascular and cerebrovascular responses to hypoxia were assessed using a multistep hypoxic design (4). In that study, hypocapnic hypoxia was shown to blunt cerebrovascular and cardiovascular sensitivities to hypoxia. However, the multistep approach did not allow the investigation of the time course of cerebrovascular and cardiovascular adaptation to hypoxia. Taken together, these data indicate a key role
of arterial hypocapnia, but highlight the need to further investigate the dynamic cardiovascular effects of hypoxia in the presence of hypocapnia.

The present investigation was part of a larger, multifaceted study comparing the dynamic cardiorespiratory responses to isocapnic versus poikilocapnic hypoxia in humans. In a previous paper we showed that the control of arterial PCO$_2$ critically affected dynamic respiratory responses during systemic hypoxia (45). In this context, it appears that the concomitant alkalosis associated with poikilocapnic hypoxia blunts the overall ventilatory response and influences ventilatory components, but does not play a role in the pattern of ventilatory adaptation to hypoxia. It remains unclear whether alkalosis affects the dynamic nature of the cardiovascular response to hypoxia similarly.

Thus, the current study investigates dynamic cardiovascular and cerebrovascular responses to hypoxia, as influenced by changes in arterial PCO$_2$ in the hypocapnic range. Furthermore, we examined the influence of respiration on cardiovascular control by combining the novel data and analyses on cardiorespiratory interaction presented in the current paper with those previously published respiratory observations (45).

We utilized single step hypoxic exposures with and without controlled PCO$_2$ to separate the effects of predominant hypoxia from those of concomitant hypocapnia. Further, hypoxia was maintained during both conditions for a duration of 20 min such that the temporal aspects of the cardiovascular responses could be investigated. Though previous studies have investigated the affects of alkalosis on cardiovascular function
during hypoxia, to our knowledge a rigorous comparison of the dynamic characteristics of the cardiovascular and cerebrovascular responses to poikilocapnic and isocapnic hypoxia has not been conducted in humans.

We hypothesized that the hypoxic stimulus would influence the shape of the dynamic pattern of cardiovascular and cerebrovascular responses, while hypocapnic alkalosis would act to suppress these patterns. Additionally, we predicted that the profiles of the cardiovascular and cerebrovascular responses undergo adaptation over time such that as hypoxia progresses a gradual fall in HR, mean arterial pressure (MAP) and CBF ensues. We speculate that this adaptation to hypoxia might be mediated by a cardioventilatory interaction, associated with the phenomenon of hypoxic ventilatory decline (HVD).
METHODS

Subjects

Ten healthy male subjects (25.7 ± 4.2 yrs, mean ± SD) participated in this study. All subjects provided informed written consent after receiving verbal and written instructions outlining the experimental procedures. Participants were not taking any medications, all were non-smokers, and none had any history of cardiovascular or respiratory disease. This study was approved by the Conjoint Health Research Ethics Board at the University of Calgary (Grant ID: 15671), and conforms to the standards set by the Declaration of Helsinki.

Protocol

Experiments were conducted at an elevation of 1,103 m and a barometric pressure of 665 ± 5 Torr. Subjects abstained from caffeine, alcohol and strenuous exercise for 12 hrs prior to testing. During experimentation, subjects took part in two randomized protocols separated by a 40 min rest period.

Prior to each protocol, subjects’ resting $P_{ET}O_2$ and $P_{ET}CO_2$ were measured for ~10 min with the subject in a comfortable semi-supine position. Respired gas was sampled continuously (20 ml·min⁻¹) via a small bore catheter (0.3 mm internal diameter) and analyzed for $PO_2$ and $PCO_2$ by mass spectrometer (AMIS 2000, Innovision, Odense, Denmark). Values for $PO_2$ and $PCO_2$ were sampled by computer every 10 ms, and $P_{ET}O_2$ and $P_{ET}CO_2$ were identified and recorded for each breath using a computer and dedicated software (Chamber v2.10, University Laboratory of Physiology, Oxford, UK).
Each protocol began with a 10 min baseline period during which the subject breathed normally through a facemask which allowed for natural mouth and/or nasal breathing (Model 16709, ResMed Corp, Poway, CA, USA). Accurate control of end-tidal gases was achieved using the technique of dynamic end-tidal forcing (4, 38, 39) and dedicated software (BreatheM v2.35, University Laboratory of Physiology, Oxford, UK).

After 10 min of euoxia (P_{ETO2} ~ 88 Torr), P_{ETO2} was decreased within 2-3 breaths to 45 Torr. During an isocapnic hypoxic protocol (IH), P_{ETCO2} was held constant at +1 Torr above resting (45). During a poikilocapnic hypoxic protocol (PH), P_{ETCO2} was allowed to vary naturally. Hypoxia was maintained for 20 minutes, after which period P_{ETO2} was returned to 88 Torr for 10 minutes.

**Cardiovascular Measurements**

Backscatter Doppler signals from the right middle cerebral artery (MCA) were measured continuously using a 2-MHz pulsed Doppler ultrasound system (PCDOP 842, SciMed) using previously published methods and criteria (1, 32, 34). Briefly, the MCA was insonated through the right temporal window superior to the zygomatic arch. Focal depth and probe angle were varied to maximize the peak Doppler frequency shift. Instrumentation was carried out by the same investigator for all subjects. Our index of flow (\( \nabla V \)) was calculated as the mean of the peak flow velocity envelope on a beat-by-beat basis. The total power spectrum signal was also collected as a representation of vessel cross-sectional area (5, 7). MAP, systolic blood pressure (SBP) and diastolic blood pressure (DBP) were calculated from the blood pressure waveform on a beat-by-
beat basis using finger photoplethysmography (Portapress, TPD Biomedical Instrumentation, Delft, The Netherlands). MAP was calculated as the area under the blood pressure waveform with the peak and the nadir representing SBP and DBP respectively. HR was calculated from a standard three-lead ECG (Micromon 7142B, Kontron Medical, Milton Keynes, UK).

Data Analysis

One minute averages were calculated for all variables immediately prior to the onset of hypoxia (time = -1 min), every 5 minutes during hypoxia (time = +5, +10, +15 and +20 min) and 5 minutes post hypoxia (time = +25 min). A one minute average was also determined at the time point corresponding to the subject-specific nadir of the $\nabla p$ response during PH. This time point was also identified during the IH protocol for comparison between conditions. An index of cerebral vascular resistance was calculated from $\nabla p$ and MAP data.

To express cardiovascular gains as linear functions of the hypoxic stimulus, $P_{ETO2}$ was converted to a calculation of $O_2$ saturation ($S\text{c}O_2$) (42). Use of $S\text{c}O_2$ avoided methodological limitations associated with pulse oximetry during conditions where changes finger blood flow may influence the accuracy of measurement (49). The gains of the acute cardiovascular response to hypoxia were calculated for $\nabla p$ ($AHR_{VP}$), MAP ($AHR_{MAP}$) and HR ($AHR_{HR}$) using the following indices:

$$AHR_{VP} = \frac{\Delta \nabla p}{\Delta S\text{c}O_2} \tag{2}$$

$$AHR_{MAP} = \frac{\Delta MAP}{\Delta S\text{c}O_2} \tag{3}$$

$$AHR_{HR} = \frac{\Delta HR}{\Delta S\text{c}O_2} \tag{4}$$
All delta values were calculated in relation to the time point immediately prior to the onset of hypoxia (Time = -1 min).

A second, objective, mathematical approach was also used to analyze $\nabla p$ data. The mathematical model described by Poulin and Robbins (34) was applied to the isocapnic data to corroborate our manually derived indices. Due to a brief gap in data collection (~10 sec), data for one subject could not be analyzed using this approach. As such, modeling data represents 9 of 10 subjects. This anomaly did not influence the mean values reported elsewhere.

**Statistical Analysis**

All cardiovascular data were analyzed using a multivariate repeated measures design, with two parallel conditions compared using pre-planned contrasts. To account for multiple comparisons ($c$), P-values were corrected using the chosen comparison-wise error rate ($\alpha$, 0.05) and the calculated experiment-wise error rate ($\alpha_e$) (19):

$$P^i = \alpha \left( \frac{P^0}{\alpha^i} \right)$$

$$\alpha^i = \frac{\alpha_e}{c}$$

$$\alpha_e = 1 - (1 - \alpha)^c$$

Where, $P^0$ and $P^i$ represent the original and corrected P-values respectively and $\alpha^i$ represents the adjustment factor based on the chosen level of significance. The number of multiple comparisons differed with the variable analyzed.

Relationships between variables were investigated using Pearson correlation analysis. All statistical analyses were performed using SPPS (v13.0, SPSS Inc.). Significance was set at $P^i < 0.05$. Data are expressed as means ± SD.
RESULTS

Mean traces of end-tidal PO₂ and PCO₂, indicating gas control, during both protocols and the temporal profiles of ventilation (Vₑ) and for all cardiovascular variables, expressed as percentages relative to baseline, are illustrated in Figure 1, absolute values for cardiovascular variables at relevant time points are shown in Table 1.

Heart Rate

HR was increased from 64.4 ± 10.7 to 84.3 ± 10.3 beats min⁻¹ during IH (+32.5 ± 15.5 %, P < 0.001) and from 62.2 ± 11.7 to 80.1 ± 15.4 bpm (+29.2 ± 10.6 %, P < 0.001) during PH, at the nadir time point, but diminished to 76.4 ± 12.0 bpm (P < 0.05) and 72.5 ± 12.5 bpm (P < 0.001) respectively by time = +20 min. This is shown as a decline in AHRHR over time during both IH and PH, with initial values of 1.32 ± 0.47 bpm·%⁻¹ desaturation and 1.07 ± 0.41 bpm·%⁻¹ desaturation at the nadir time point respectively, declining to 0.75 ± 0.24 bpm·%⁻¹ desaturation (P < 0.05) during IH and 0.64 ± 0.23 bpm·%⁻¹ desaturation (P < 0.01) during PH at time = +20 min. HR gains across time during IH and PH are shown in Table 2. The heart rate response to hypoxia exhibited a strikingly similar pattern to that of Vₑ. Correlation analysis of the relationship between Vₑ and HR indicated a modest, but significant relationship during both IH (r = 0.62, P < 0.001) and PH (r = 0.31 P < 0.01).

Blood Pressure

There was a modest increase in MAP during both protocols. However, while the increase in MAP occurred immediately following the initiation of IH, the response during
PH was delayed. During IH, MAP rose from 68.7 ± 11.7 to 74.9 ± 11.9 mmHg at the nadir time point, but was not elevated until time = +5 min during PH (67.7 ± 7.6 to 72.5 ± 9.2 mmHg). Subsequently, the increase in MAP was maintained throughout hypoxia during both conditions. At the offset of hypoxia MAP returned toward baseline during IH. However, during PH MAP remained elevated with respect to baseline at time = +25 min (76.7 ± 13.1 mmHg, P < 0.05). Calculation of AHR_{MAP} indicated a consistent gain across all time points during IH (~0.37 mmHg·%^{-1} desaturation). During PH, AHR_{MAP} was significantly lower than during IH at the Nadir time point (0.05 ± 0.29 mmHg·%^{-1} desaturation vs. 0.39 ± 0.48 mmHg·%^{-1} desaturation, P < 0.05), rising to a similar level as IH by time = +5 min. No further differences were observed between conditions.

Cerebral Blood Flow

Our index of MCA cross sectional area (Power) was unchanged from baseline during both conditions. Therefore, \( V_P \) was used as our index of cerebral blood flow. During IH, \( V_P \) was significantly elevated throughout the hypoxic exposure and remained modestly elevated at time = +25 min 102.5 ± 2.8 % (+1.9 ± 1.4 cm·s^{-1}, P < 0.01). Alternatively, the response during PH was biphasic, with an initial decrease in \( V_P \) (94.0 ± 5.3%, -3.1 ± 2.7 cm·s^{-1}, P < 0.01) reaching its nadir at 79 ± 26 seconds. This was followed by a subsequent rise in \( V_P \), becoming significantly elevated above baseline by time = +5 min, 103.2 ± 5.0 % (+2.0 ± 2.4 cm·s^{-1}, P < 0.01). As in IH, \( V_P \) following PH remained modestly increased above baseline (102.4 ± 6.2 %, +1.8 ± 2.8 cm·s^{-1}, P < 0.05).
The nadir of the \( \nabla P \) response during PH was found to correspond closely with the timing of the peak ventilatory response during PH (80 ± 42 seconds). When correlation analyses of the change in \( \nabla P \) versus changes in \( V_E \) or PETCO₂ were performed, no significant relationships were found (\( r = -0.08, \) NS and \( r = -0.09, \) NS). However, upon removing one subject who exhibited no change in \( \nabla P \) at the onset of PH, the relationship between \( \nabla P \) and \( V_E \) became significant (\( r = -0.68, P < 0.05 \)), though the relationship with PETCO₂ remained non-significant (\( r = -0.2, \) NS). Further analysis of the relationships between the change in \( \nabla P \) and \( V_E \) and PETCO₂ could not explain the subsequent rise in \( \nabla P \) during PH.

No differences in middle cerebral artery resistance (or conductance) were observed during IH. However, during PH an increase in resistance (a decrease in conductance) was observed early in hypoxia, corresponding to the nadir of the \( \nabla P \) response (\( P = 0.031 \) compared to baseline). This increase in resistance was subsequently normalized by time = + 5 minutes as \( \nabla P \) continued to rise, becoming equivalent to that observed during IH by time = +10 min.

The AHR\(_{V_P}\) during IH was 0.29 ± 0.25 cm·s\(^{-1} \)·%\(^{-1}\) desaturation at the nadir time point, and remained unchanged throughout the hypoxic exposure. Alternatively, the AHR\(_{V_P}\) during PH exhibited an increase across time with an initial nadir sensitivity of -0.25 ± 0.19 cm·s\(^{-1} \)·%\(^{-1}\) desaturation increasing to 0.08± 0.16 cm·s\(^{-1} \)·%\(^{-1}\) desaturation at time = +5 min (\( P < 0.001 \) with respect to nadir) and further rose to 0.28 ± 0.22 cm·s\(^{-1} \)·%\(^{-1}\) desaturation at time = +10 min.
desaturation at time = +20 min (P < 0.001 with respect to nadir). The relationships of AHR\textsubscript{Vp} between conditions and across time, are shown in Table 2.

Modeled Response to Isocapnic Hypoxia

\( \nabla P \) data were modeled for nine of 10 subjects to provide a secondary, objective verification of our derived sensitivities. The steady state \( \nabla P \) gain in response to hypoxia (\( g_h \)) was 0.32 ± 012 cm·s\(^{-1}\)·%\(^{-1}\) desaturation with a time delay (\( T_d \)) and time constant (\( \tau_{on} \)) of 9.1 ± 8.7 s and 81.2 ± 86.2 s respectively. Correlation analysis of the relationship between \( g_h \) and AHR\textsubscript{Vp} at time = +20 min (\( n = 9 \)), showed a strong relationship (\( R = 0.90, P = 0.001 \)) between the two measures of hypoxic gain, corroborating our manually derived calculations.
DISCUSSION

Main Findings

To our knowledge this is the first study to investigate the dynamic temporal cardiovascular responses to both isocapnic and poikilocapnic hypoxia in humans. The investigation of adaptation to poikilocapnic hypoxia is important, as this represents the in vivo conditions associated with altitude. While the heart rate response was the same between IH and PH, significant differences in the dynamic profiles of the MAP and $\nabla p$ responses were observed. MAP was increased during both conditions, with the response developing later in hypoxia during PH. The $\nabla p$ response during IH exhibited a typical increase occurring rapidly after the onset of hypoxia, which was then maintained for the duration of the exposure. Alternatively, the response during PH was biphasic, with an initial decrease in cerebral blood flow followed by a subsequent recovery which then became significantly elevated with respect to baseline, and equivalent to the IH condition, by Time = +10min.

Heart Rate Response

Heart rate was shown to increase substantially at the initiation of both IH and PH, with a subsequent progressive decline with time. This response pattern has been shown previously during isocapnic protocols (46, 47), with steady state gains (at ~20 min) very similar to our own (30). Studies of isolated carotid body stimulation in animals document a reflex bradycardia when ventilation is constrained (31), and no change (47) or a decrease (11) in HR is observed during hypoxia in humans when breathing is controlled. The tachycardia exhibited by the systemic response to hypoxia is therefore
related to the stimulation of lung mechanoreceptors which cause HR to increase via parasympathetic withdrawal (30). This study confirms the relationship between $V_E$ and HR. In this way, the progressive decline in HR with time, despite a maintained level of hypoxia, may be linked to the development of hypoxic ventilatory decline, wherein a decline in ventilation results in a gradual decrease in HR as we have documented. Indeed, in a study of longer duration, the secondary rise in ventilation associated with the onset of hypoxic acclimatization was mirrored by similar changes in HR (46). Further, during sustained hypercapnia ventilation is elevated with no evidence of ventilatory decline as seen during prolonged hypoxic exposures (33). The increase in heart rate is similar, remaining consistently elevated throughout sustained hypercapnic exposures (27).

These direct linkages between ventilation and heart rate are not surprising in light of respiratory sinus arrhythmia, where ventilation ‘gates’ heart rate (13). However, in the present study no significant difference in HR was observed between IH and PH, whereas ventilation was significantly higher during IH. While this disparity may tend to contradicts a major role of lung stretch receptors, two factors may explain these results. Firstly, a recent paper by Rutherford et al. (40) proposes an additional tachycardic effect due to hypocapnic coronary vasoconstriction. Secondly, blunting of the chemosensory response to hypoxia during hypocapnia could be expected to result in a decreased reflex bradycardia, therefore a smaller $V_E$ may act to withdraw parasympathetic tone and cause HR to rise to the same extent as during isocapnia. This may help explain the equivalency in HR responses during IH and PH, despite differing ventilatory responses (45).
Interestingly, the above relationship is strongest with respect to changes in total ventilation, not changes tidal volume. This would tend to indicate that rate of lung stretch, not just volume, also plays a role in the tachycardic response to hypoxia.

Blood Pressure Response

In the present study our subjects exhibited mean arterial blood pressures of approximately 70 mmHg and systolic and diastolic pressures of ~110 mmHg and ~55 mmHg respectively at rest. These values are lower than the stereotypical norms of 93 mmHg, 120 mmHg and 80 mmHg for mean, systolic and diastolic pressures, respectively. There are a number of factors which may contribute to this apparent difference. First, the subjects taking part in the present investigation were all young healthy males who were regularly active in various cardiovascular exercises and may be expected to have slightly lower resting blood pressures. Second, the extensive research of Imholz et al. has assessed the accuracy of photoplethysmography during many interventions (for reviews see 21, 22). Their research indicates that various devices utilizing this technique, including the Portapres system used in the present study, may tend to underestimate both mean and diastolic pressures in a range of -1.6 ± 8 mmHg (22). However, this same research shows that these devices accurately track broad changes in arterial blood pressure when compared to intra-arterial measures. In the context of the present study, our values for mean and diastolic blood pressure may be slightly below expected values, but we are confident that the temporal pattern of changes in blood pressure are an accurate representation of true blood pressure.
While the blood pressure response to isocapnic hypoxia is the result of a complex interaction between neural and local effects on vascular tone as well as the influence of cardiac output, a modest increase in MAP has been documented in response to systemic hypoxia in humans (16, 31). Similarly, in the present study, MAP was elevated during both IH and PH, but, with the response developing earlier during the isocapnic condition. The disparity in the response dynamics during PH may be attributable to the concomitant hypocapnia. Both Richardson et al. (37) and Kontos et al. (28) have documented a biphasic blood pressure response during hyperventilation induced hypocapnia, with a transient decrease within the first 1-5 minutes due to histamine mediated decreases in vascular resistance (28) and subsequent rise to baseline levels over the next 5 minutes due to the local vasoconstrictor actions of alkalosis (12). Though hypoxia is also a vasodilating agent, it also causes a large increase in sympathetic vasoconstrictor nerve activity (52). In this way, the combined effects of hypocapnia and hypoxia may result in a blood pressure response which is suppressed early in hypoxia, but becomes significantly elevated with longer exposure. The steady state gains (Time = +20 min) of the response were similar to that reported previously during IH (3) and PH (4) from our laboratory.

Cerebral Blood Flow Response

To accurately study cerebral blood flow dynamics, PO2 and PCO2 must be finely controlled. The technique of end-tidal gas forcing has been shown to significantly reduce variability in middle cerebral artery flow (17), in part by controlling variations in PO2 and PCO2, which can have profound effects on the cerebral circulation (20). In the present
study, the response to IH was characterized by an increase in cerebral blood flow with a steady state gain of ~0.3 cm·s$^{-1}$ per % desaturation and a time constant of ~81 s, whereas the response to PH was biphasic. A recent study by Ainslie et al. has also documented a initial decrease in $\nabla P$ at the onset of PH (2). However, while $\nabla P$ returned towards baseline with maintained exposure, they did not document a subsequent rise in $\nabla P$ as we have reported in the present investigation.

In our study, no changes in middle cerebral artery resistance (or conductance) were observed during IH. These data would suggest that the flow profile during IH is mediated via changes in perfusion, and not hypoxic vasodilation in the brain. This is counter to previous reports indicating a decrease in cerebral vascular resistance (8, 25, 43) during IH and data indicating that the level of hypoxia utilized in the present study exceeds the threshold for hypoxic cerebral vasodilation (15, 25). However, our hypoxic stimulus may have been potent enough to cause a significant rise in cardiac output greater than the vasodilation occurring in the brain, masking any changes in vascular resistance. However, without a measure of cardiac output in the present study this remains unclear. During PH, the onset of hypoxia was characterized by an increase in cerebral vascular resistance, causing a decrease in blood flow. By 10 min the change in resistance was normalized, and blood flow rose significantly. As blood pressure was not decreased at the onset of hypoxia during the PH condition, the initial increase in resistance may be mediated by a hypocapnia induced constriction in the brain. However, we were unable to document any significant relationships between changes in $\nabla P$ and changes $\text{PETO}_2$. That being said, our indirect measure of arterial CO$_2$ may not accurately represent changes in
brain tissue pH. The subsequent normalization of middle cerebral artery resistance, and an increase in blood flow equivalent to the IH condition by time = +10 minutes, would appear to indicate an elimination of any hypocapnic constriction and a dominance of perfusion related mechanisms similar to that seen during IH.

Support for the role of decreased brain PCO₂/pH at the onset of PH comes from the similarity of the V̇p profile compared to that reported during hyperventilation induced hypocapnia (14, 35). The cerebral blood flow response to euoxic hypocapnia is characterized by an initial decrease in V̇p, followed by a secondary slow rise over time similar to what we report during PH. If we express the percentage reduction in V̇p at the onset of PH as a function of P_ETCO₂, a nadir sensitivity of -2.13 %·Torr⁻¹ is calculated. This is very similar to previous investigations of the cerebrovascular responses to hypocapnia (14, 35). However, though V̇p exhibits a progressive rise during euoxic hypocapnia, it does not return to baseline levels (14, 35), whereas we document significantly elevated V̇p by Time = +20 min. The near equivalency of V̇p during IH and PH at Time = +20 min indicates that the hypoxic stimulus dominates late in the PH exposure. The resultant V̇p-time curve represents an interaction between these two competing variables.

The use of a secondary, objective mathematical model applied to the IH data served to verify our derivations of cerebrovascular sensitivities. The complexity of the response occurring during PH precludes the use of this model on these data. However, based on
the strong correlation between modeled gain ($g_b$) and AHR$_{VP}$ during IH we are confident that our calculation of AHR$_{VP}$ during PH is also accurate.

*Methodological Considerations*

The present study was conducted at an altitude of ~1100m. This must be taken into consideration when interpreting our results, particularly considering seven of ten subjects were native to altitudes lower than 500m and or returned to near sea-level altitude multiple times yearly. As such, we could expect that our subjects may be representative of sojourners, but not natives, of mild altitude. Previous studies have shown that acclimatization to both mild (1,560m) (2) and moderate (3,810m) (23) altitude is characterized by augmented cardiovascular gains. As such, we may expect our cardiovascular gains to be slightly higher than those reported at near sea-level.

The use of transcranial Doppler (TCD) ultrasound has been used extensively in clinical and research settings as a non-invasive method of measuring CBF. However, this is based on some basic assumptions which must be taken into consideration when interpreting results (26). Firstly, here we have used VP as our index of flow while assuming that cross-sectional area of the MCA remains constant. We have based this assumption on previously published data indicating no appreciable change in MCA caliber during similar interventions as used in the present study (41). Further, the total power spectrum of the Doppler signal has been previously shown to be an accurate representation of vessel cross-sectional area (5, 7) and in keeping with the results of the present investigation, does not change during the chosen level of hypoxia (36). Secondly,
we have assumed that $V_p$ is the most accurate representation of flow velocity in the MCA. This is in keeping with previously published data (24) and the observation that the intensity weighted mean velocity exhibited the same responses as $V_p$ (not shown). As such, we believe that $V_p$ represents an accurate index of MCA blood flow in the present study.

The present study sought to investigate the dynamic cardiovascular responses to both isocapnic and poikilocapnic hypoxia. This required a prolonged and finely controlled stimulus. The use of dynamic end-tidal forcing, allowed for precise control of end-tidal (~arterial) PO$_2$ and PCO$_2$ on a breath-by-breath basis. Recent work from our lab using similar methods has shown this particular technique to be precise to within ±0.6 Torr for PETCO$_2$ and ±2.0 Torr for PETO$_2$ (48). In this way, we were certain that the delivered stimulus was consistent and accurate, avoiding oscillations which could interfere with analysis and interpretation. However, one limitation of our experimental approach is its use of one specific hypoxic stimulus. As such, data from this particular protocol may not be representative of the response at more extreme or less severe hypoxic levels.

Summary

The alterations in cardiovascular gains over time observed here may not be specific to hypoxia per se. From these data we provide evidence of the effect of ventilation and arterial or tissue PCO$_2$ / pH in the cardiovascular and cerebrovascular adaptation to sustained hypoxia. Furthermore, the local and neural mechanisms of hypoxia may also independently adapt. The cerebrovascular response to poikilocapnic (hypocapnic)
hypoxia contains an early response, which appears to be mediated predominantly by the decrease in PCO$_2$, followed by a secondary response, mediated predominantly by hypoxia. However, these effects appear to be due to an increase in cerebral perfusion, not a change in cerebral resistance. As such, the overall response likely involves multiple, possibly interacting, mechanisms. The protocols in the present study, specifically the inclusion of a poikilocapnic design, are more representative of *in vivo* environments and illustrate the dynamic nature by which hypocapnic alkalosis critically alters the cardiovascular and cerebrovascular responses to hypoxia.
ACKNOWLEDGMENTS

We thank Dr. P.N. Ainslie and Dr. J.C. Kolb for their input and feedback throughout the study and we extend our gratitude to Professor P.A. Robbins for assistance in setting up the technique of dynamic end-tidal forcing in Calgary.

GRANTS

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REFERENCES


**Figure 1:** Mean values (n=10) of end-tidal gases, ventilation and cardiovascular variables during isocapnic hypoxia (solid lines) and poikilocapnic hypoxia (dashed lines). Cardiovascular variables are expressed as a percentage of baselines. Panel A: End-tidal PO$_2$ ($P_{ETO_2}$). Panel B: End-tidal PCO$_2$ ($P_{ETCO_2}$). Panel C: Ventilation (VE). Panel D: Heart rate (HR). Panel E: Mean arterial blood pressure (MAP). Panel F: Middle cerebral artery peak velocity ($V_p$).
Table 1: Absolute values for end tidal gases, ventilation and cardiovascular variables during isocapnic and poikilocapnic hypoxia.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Condition</th>
<th>-1 min</th>
<th>Nadir</th>
<th>5 min</th>
<th>10 min</th>
<th>15 min</th>
<th>20 min</th>
<th>Post 5 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>PETO₂ (Torr)</td>
<td>Isocapnia</td>
<td>88.9 ± 1.7</td>
<td>46.0 ± 1.0 *&lt;sup&gt;c&lt;/sup&gt;</td>
<td>44.7 ± 0.5&lt;sup&gt;c&lt;/sup&gt;</td>
<td>44.6 ± 0.5&lt;sup&gt;c&lt;/sup&gt;</td>
<td>45.2 ± 0.9&lt;sup&gt;c&lt;/sup&gt;</td>
<td>45.4 ± 2.3&lt;sup&gt;c&lt;/sup&gt;</td>
<td>90.1 ± 1.8 ‡&lt;sup&gt;†&lt;/sup&gt;</td>
</tr>
<tr>
<td>Poikilocapnia</td>
<td>88.1 ± 0.8</td>
<td>44.5 ± 1.6&lt;sup&gt;c&lt;/sup&gt;</td>
<td>44.0 ± 0.5&lt;sup&gt;c&lt;/sup&gt;</td>
<td>44.0 ± 1.6&lt;sup&gt;c&lt;/sup&gt;</td>
<td>44.5 ± 1.9&lt;sup&gt;c&lt;/sup&gt;</td>
<td>46.1 ± 2.0&lt;sup&gt;c&lt;/sup&gt;</td>
<td>87.3 ± 4.2</td>
<td></td>
</tr>
<tr>
<td>PETCO₂ (Torr)</td>
<td>Isocapnia</td>
<td>37.2 ± 1.8</td>
<td>37.0 ± 2.2</td>
<td>37.3 ± 1.9</td>
<td>37.3 ± 1.9</td>
<td>37.1 ± 2.0</td>
<td>37.3 ± 1.9</td>
<td>36.9 ± 2.3</td>
</tr>
<tr>
<td>Poikilocapnia</td>
<td>36.4 ± 2.5</td>
<td>32.0 ± 2.4 ‡&lt;sup&gt;c&lt;/sup&gt;</td>
<td>31.8 ± 2.4 ‡&lt;sup&gt;c&lt;/sup&gt;</td>
<td>32.1 ± 2.7 ‡&lt;sup&gt;c&lt;/sup&gt;</td>
<td>32.3 ± 2.6 ‡&lt;sup&gt;c&lt;/sup&gt;</td>
<td>32.8 ± 2.6 ‡&lt;sup&gt;c&lt;/sup&gt;</td>
<td>35.9 ± 2.0</td>
<td></td>
</tr>
<tr>
<td>VE (L·min⁻¹)</td>
<td>Isocapnia</td>
<td>12.6 ± 2.4</td>
<td>40.6 ± 11.6 †&lt;sup&gt;a&lt;/sup&gt;</td>
<td>32.7 ± 12.0 †&lt;sup&gt;a&lt;/sup&gt;</td>
<td>24.0 ± 7.2 †&lt;sup&gt;a&lt;/sup&gt;</td>
<td>12.7 ± 2.6&lt;sup&gt;b&lt;/sup&gt;</td>
<td>12.5 ± 4.0&lt;sup&gt;a&lt;/sup&gt;</td>
<td>11.7 ± 2.7&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Poikilocapnia</td>
<td>10.0 ± 2.7</td>
<td>19.6 ± 6.2 &lt;sup&gt;c,e,h,k,o&lt;/sup&gt;</td>
<td>13.4 ± 2.8&lt;sup&gt;c,m&lt;/sup&gt;</td>
<td>12.7 ± 2.6&lt;sup&gt;b&lt;/sup&gt;</td>
<td>12.5 ± 4.0&lt;sup&gt;a&lt;/sup&gt;</td>
<td>11.7 ± 2.7&lt;sup&gt;a&lt;/sup&gt;</td>
<td>9.4 ± 3.4</td>
<td></td>
</tr>
<tr>
<td>HR (bpm)</td>
<td>Isocapnia</td>
<td>64 ± 11</td>
<td>84 ± 10&lt;sup&gt;c&lt;/sup&gt;</td>
<td>82 ± 12&lt;sup&gt;c&lt;/sup&gt;</td>
<td>80 ± 13&lt;sup&gt;c&lt;/sup&gt;</td>
<td>76 ± 11&lt;sup&gt;c,e&lt;/sup&gt;</td>
<td>76 ± 12&lt;sup&gt;c,d&lt;/sup&gt;</td>
<td>60 ± 10&lt;sup&gt;a&lt;/sup&gt;</td>
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<tr>
<td>Poikilocapnia</td>
<td>62 ± 11</td>
<td>80 ± 15&lt;sup&gt;c&lt;/sup&gt;</td>
<td>79 ± 12&lt;sup&gt;c&lt;/sup&gt;</td>
<td>75 ± 12&lt;sup&gt;c,d&lt;/sup&gt;</td>
<td>73 ± 12&lt;sup&gt;c,d&lt;/sup&gt;</td>
<td>73 ± 13&lt;sup&gt;c,e&lt;/sup&gt;</td>
<td>60 ± 12</td>
<td></td>
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<td>SBP (mmHg)</td>
<td>Isocapnia</td>
<td>110 ± 16</td>
<td>121 ± 18&lt;sup&gt;a&lt;/sup&gt;</td>
<td>122 ± 17&lt;sup&gt;a&lt;/sup&gt;</td>
<td>123 ± 15&lt;sup&gt;b&lt;/sup&gt;</td>
<td>121 ± 15&lt;sup&gt;b&lt;/sup&gt;</td>
<td>121 ± 16&lt;sup&gt;b&lt;/sup&gt;</td>
<td>116 ± 14</td>
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<tr>
<td>Poikilocapnia</td>
<td>108 ± 11</td>
<td>115 ± 13&lt;sup&gt;a&lt;/sup&gt;</td>
<td>118 ± 16&lt;sup&gt;b&lt;/sup&gt;</td>
<td>120 ± 14&lt;sup&gt;c,d&lt;/sup&gt;</td>
<td>121 ± 14&lt;sup&gt;b,d&lt;/sup&gt;</td>
<td>122 ± 13&lt;sup&gt;b&lt;/sup&gt;</td>
<td>123 ± 19&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>DBP (mmHg)</td>
<td>Isocapnia</td>
<td>53 ± 11</td>
<td>57 ± 11</td>
<td>59 ± 10&lt;sup&gt;b&lt;/sup&gt;</td>
<td>58 ± 10&lt;sup&gt;b&lt;/sup&gt;</td>
<td>56 ± 10&lt;sup&gt;a&lt;/sup&gt;</td>
<td>57 ± 10&lt;sup&gt;a&lt;/sup&gt;</td>
<td>56 ± 10&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Poikilocapnia</td>
<td>52 ± 7</td>
<td>52 ± 9</td>
<td>56 ± 8&lt;sup&gt;b,c&lt;/sup&gt;</td>
<td>55 ± 8&lt;sup&gt;a,c&lt;/sup&gt;</td>
<td>55 ± 8&lt;sup&gt;a,c&lt;/sup&gt;</td>
<td>56 ± 7&lt;sup&gt;a&lt;/sup&gt;</td>
<td>59 ± 10&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
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<tr>
<td>MAP (mmHg)</td>
<td>Isocapnia</td>
<td>69 ± 12</td>
<td>75 ± 12&lt;sup&gt;b&lt;/sup&gt;</td>
<td>76 ± 11&lt;sup&gt;b&lt;/sup&gt;</td>
<td>75 ± 10&lt;sup&gt;b&lt;/sup&gt;</td>
<td>74 ± 10&lt;sup&gt;a&lt;/sup&gt;</td>
<td>74 ± 10&lt;sup&gt;a&lt;/sup&gt;</td>
<td>72 ± 10</td>
</tr>
<tr>
<td>Poikilocapnia</td>
<td>68 ± 8</td>
<td>69 ± 10</td>
<td>73 ± 9&lt;sup&gt;b,d&lt;/sup&gt;</td>
<td>72 ± 9&lt;sup&gt;a,d&lt;/sup&gt;</td>
<td>72 ± 10&lt;sup&gt;a,d&lt;/sup&gt;</td>
<td>74 ± 8&lt;sup&gt;a&lt;/sup&gt;</td>
<td>77 ± 13&lt;sup&gt;a&lt;/sup&gt;</td>
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<tr>
<td>V̇P (cm·s⁻¹)</td>
<td>Isocapnia</td>
<td>62 ± 14</td>
<td>66 ± 13 †&lt;sup&gt;a&lt;/sup&gt;</td>
<td>67 ± 14&lt;sup&gt;*,c&lt;/sup&gt;</td>
<td>67 ± 13&lt;sup&gt;c&lt;/sup&gt;</td>
<td>68 ± 13&lt;sup&gt;c&lt;/sup&gt;</td>
<td>67 ± 13&lt;sup&gt;c&lt;/sup&gt;</td>
<td>64 ± 13&lt;sup&gt;b&lt;/sup&gt;</td>
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<tr>
<td>Poikilocapnia</td>
<td>61 ± 15</td>
<td>58 ± 16</td>
<td>63 ± 15&lt;sup&gt;b,f&lt;/sup&gt;</td>
<td>65 ± 14&lt;sup&gt;b,f,h&lt;/sup&gt;</td>
<td>66 ± 14&lt;sup&gt;c,f,h&lt;/sup&gt;</td>
<td>65 ± 16&lt;sup&gt;b,f,h&lt;/sup&gt;</td>
<td>63 ± 16</td>
<td></td>
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<tr>
<td>CVR</td>
<td>Isocapnia</td>
<td>1.14 ± 0.16</td>
<td>1.15 ± 0.16</td>
<td>1.15 ± 0.15</td>
<td>1.14 ± 0.18</td>
<td>1.11 ± 0.15&lt;sup&gt;g&lt;/sup&gt;</td>
<td>1.12 ± 0.16&lt;sup&gt;g&lt;/sup&gt;</td>
<td>1.15 ± 0.16</td>
</tr>
<tr>
<td>Poikilocapnia</td>
<td>1.16 ± 0.28</td>
<td>1.27 ± 0.35&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.20 ± 0.29</td>
<td>1.15 ± 0.27&lt;sup&gt;g&lt;/sup&gt;</td>
<td>1.14 ± 0.28&lt;sup&gt;d,h&lt;/sup&gt;</td>
<td>1.17 ± 0.29</td>
<td>1.28 ± 0.34</td>
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</table>

Definition of terms: PETO₂, End-tidal O₂; PETCO₂, End-tidal CO₂; VE, ventilation; HR, heart rate; SBP, systolic blood pressure; DBP, diastolic blood pressure; MAP, mean arterial pressure; V̇P, peak middle cerebral artery blood flow velocity; CVR, index of cerebral vascular resistance. Values are expressed as mean ± SD. Times are in reference to the onset of hypoxia. Nadir corresponds to the time associated with the initial decrease in V̇P during PH. For VE, Nadir corresponds to the maximal ventilatory response at the onset of hypoxia.

Significant difference between conditions: *<sup>P < 0.05</sup>, †<sup>P < 0.01</sup>, ‡<sup>P < 0.001</sup>. Significantly different from baseline (Time = -1 min), within condition: <sup>a</sup><sup>P < 0.05</sup>, <sup>b</sup><sup>P < 0.01</sup>, <sup>†</sup><sup>P < 0.001</sup>. Significantly different from Nadir, within condition: <sup>d</sup><sup>P < 0.05</sup>, <sup>i</sup><sup>P < 0.01</sup>, <sup>j</sup><sup>P < 0.001</sup>. Significantly different from Time = +5 min, within condition: <sup>e</sup><sup>P < 0.05</sup>, <sup>P < 0.001</sup>. Significantly different from Nadir, within condition: <sup>m</sup><sup>P < 0.05</sup>, <sup>n</sup><sup>P < 0.01</sup>, <sup>o</sup><sup>P < 0.001</sup>. Significantly different from Time = +15 min, within condition: <sup>P < 0.05</sup>, <sup>b</sup><sup>P < 0.01</sup>, <sup>‡</sup><sup>P < 0.001</sup>. Significantly different from Time = +20 min, within condition: <sup>‡</sup><sup>P < 0.05</sup>, <sup>‡</sup><sup>P < 0.01</sup>, <sup>‡</sup><sup>P < 0.001</sup>.
Table 2:  *Cardiovascular sensitivities during isocapnic and poikilocapnic hypoxia.*

<table>
<thead>
<tr>
<th></th>
<th>Nadir</th>
<th>+5 min</th>
<th>+10 min</th>
<th>+15 min</th>
<th>+20 min</th>
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<tr>
<td>AHR_HR (bpm·%⁻¹)</td>
<td></td>
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<td></td>
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<tr>
<td>Isocapnia</td>
<td>1.32 ± 0.47</td>
<td>1.09 ± 0.26</td>
<td>0.94 ± 0.39</td>
<td>0.73 ± 0.28</td>
<td>0.75 ± 0.24</td>
</tr>
<tr>
<td>Poikilocapnia</td>
<td>1.07 ± 0.41</td>
<td>1.00 ± 0.26</td>
<td>0.72 ± 0.23</td>
<td>0.64 ± 0.26</td>
<td>0.64 ± 0.23</td>
</tr>
<tr>
<td>AHR_MAP (mmHg·%⁻¹)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Isocapnia</td>
<td>0.40 ± 0.48</td>
<td>0.45 ± 0.37</td>
<td>0.39 ± 0.30</td>
<td>0.31 ± 0.28</td>
<td>0.32 ± 0.30</td>
</tr>
<tr>
<td>Poikilocapnia</td>
<td>0.05 ± 0.29</td>
<td>0.29 ± 0.22</td>
<td>0.26 ± 0.24</td>
<td>0.28 ± 0.27</td>
<td>0.37 ± 0.34</td>
</tr>
<tr>
<td>AHR_VP (cm·s⁻¹·%⁻¹)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Isocapnia</td>
<td>0.29 ± 0.25</td>
<td>0.35 ± 0.14</td>
<td>0.32 ± 0.14</td>
<td>0.38 ± 0.14</td>
<td>0.36 ± 0.15</td>
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<tr>
<td>Poikilocapnia</td>
<td>-0.25 ± 0.19</td>
<td>0.08 ± 0.16</td>
<td>0.21 ± 0.16</td>
<td>0.27 ± 0.14</td>
<td>0.28 ± 0.22</td>
</tr>
</tbody>
</table>

Definition of terms:  AHR_{VP}, peak blood flow velocity sensitivity to hypoxia. AHR_{HR}, heart rate sensitivity to hypoxia. AHR_{MAP}, blood pressure sensitivity to hypoxia.  All values are expressed as a change per percent desaturation and as mean ± SD.  Nadir corresponds to the time associated with the initial decrease in V̇\textsubscript{PD} during PH.

Significant difference between conditions:  *P < 0.05, †P < 0.01, ‡P < 0.01.  Significantly different from Nadir within condition:  ^P < 0.05, ^P < 0.01, ^P < 0.001.  Significantly different from Time= +5 min within condition:  *P < 0.05, *P < 0.01, *P < 0.001.