Surviving Without Oxygen: How Low Can the Human Brain Go?

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Abstract


Hypoxic cerebral vasodilation is a highly conserved physiological response coupling cerebral O2 delivery (CDO2) to metabolic demand with increasingly important roles identified for the red blood cell (sensor) and nitric oxide (effector). In the current article, we reexamine previously published cerebral blood flow (CBF) and arterial blood gas data obtained in freedivers and mountaineers, extreme athletes in whom the lowest arterial partial pressures of O2 (19–23 mmHg) and greatest extremes of carbon dioxide (16–61 mmHg) were recorded during (acute) maximal static dry apnea or (chronic) exposure to terrestrial high altitude. Data highlight compensatory increases in CBF (+96% in freedivers to +209% in mountaineers relative to normoxic baseline controls) that were sufficient to sustain CDO2 (+24% in freedivers to +183% in mountaineers) even in the face of the most severe reductions in arterial O2 content (−61% in freedivers to −9% in mountaineers) reported in the literature, consistent with the conservation of mass principle. These unique findings highlight to what extent cerebral vasodilation likely contributes toward these athletes’ extraordinary abilities to survive in such harsh environments characterized by physiological extremes of hypoxemia, alkalosis, and acidosis helping define the human brain’s remarkable limits of tolerance.

Keywords: brain; carbon dioxide; freediver; mountaineer; oxygen; vasodilation

Introduction

Paleoclimate and evolution of the human brain

Environmental pressures caused by climatic fluctuations have long been assumed to play a key role in hominin speciation and adaptation (Maslin et al., 2015). The inexorable rise in the paleoatmospheric O2 concentration throughout the Proterozoic Eon of the Precambrian period (~2500–540 million years ago) catalyzed life on Earth (Berner et al., 2007) with chemical reduction by the mitochondrial electron transport chain evolving into the primary source of adenosine triphosphate (ATP) for the respiring eukaryote (Nisbet and Sleep, 2001). The human brain exemplifies our reliance on O2 since, unlike most other organs, its evolutionary “drive for size” means that it is now committed to a continually active state, demanding a disproportionate 20% of the body’s basal O2 budget, more than 10 times that expected from its mass alone (Bailey et al., 2009a; Bailey, 2016). This obligatory requirement to process large amounts of O2 over a relatively small tissue mass is required...
to support the high rate of ATP formation to fuel the maintenance of ionic equilibria and uptake of neurotransmitters for synaptic transmission (Alle et al., 2009).

However, this obligatory high rate of \( \text{O}_2 \) consumption is associated with high “vulnerability for failure” given the brain’s paradoxically limited \( \text{O}_2 \) reserves. Indeed, assuming an average brain tissue partial pressure of \( \text{O}_2 \) (\( \text{PO}_2 \)) of \( \sim 25 \text{ mmHg} \) and lack of \( \text{O}_2 \)-binding proteins, its \( \text{O}_2 \) content is a meagre \( \sim 30 \text{ nmol/mL} \) such that given an average cerebral metabolic rate of oxygen (\( \text{CMR}_{\text{O}_2} \)) of 30 nmol/mL/s, the \( \text{O}_2 \) present would sustain metabolism for at best 1 second if blood supply were to be interrupted by anoxia (Leithner and Royl, 2014). Unable to compromise on its excessive energy budget, failure of \( \text{ATP} \)-dependent ion exchangers results in the breakdown of ionic gradients and membrane depolarization triggering a cytotoxic increase in intracellular \( \text{Ca}^{2+} \) concentration and uncontrolled release of excitatory neurotransmitters that ultimately converge in neuronal death (Lipton, 1999).

Yet, \( \text{O}_2 \) is not the only atmospheric gas to have shaped life on Earth with an equally important role identified for carbon dioxide (\( \text{CO}_2 \)), the key substrate for oxygenic photosynthesis (Cummins et al., 2014). The human brain has since evolved heightened sensitivity to \( \text{PaCO}_2/\text{H}^+ \) (more so than \( \text{PaO}_2 \)) that extends throughout the cerebrovasculature, from the large extracranial and intracranial conduit and middle cerebral arteries to the smallest pial arterioles and parenchymal vessels, prioritizing the buffering of brain tissue pH for stabilization of chemosensory and autonomic control at the level of the brainstem (Kety and Schmidt, 1948a; Willie et al., 2014). Given that the brain’s \( \text{O}_2/\text{CO}_2 \) balance is so delicate, it would therefore seem intuitive for evolution to favor defense mechanisms capable of sensing “crosstalk” between these respiratory gases and orchestrating the coordinated transmission of vasoactive signals to the cerebrovasculature coupling local cerebral \( \text{O}_2 \) delivery (\( \text{DCO}_2 \)) to tissue metabolic demand.

In the current article, we reexamine previously published cerebral blood flow (\( \text{CBF} \)) and arterial blood gas data obtained in freedivers and mountaineers, extreme athletes in whom the lowest \( \text{PaO}_2 \)’s and greatest extremes of \( \text{PaCO}_2 \) (from respiratory alkalosis in the mountaineer to acidosis in the freediver) to date have been documented in the literature. These unique datasets reveal that even at physiological, if not pathological extremes of hypoxia, alkalosis, and acidosis there remains 3% was successfully negotiated by Reinhold Messner and Peter Habeler, and the world’s highest mountain finally conquered, albeit some 54 years later. Medical opinion was equally divided when the freedivers, Jacques Mayol and Enzo Maiorca, attempted to dive below 50 m without any breathing apparatus in the late 1960s. While both survived the challenge and later went on to exceed 100 m, precisely how modern-day world record holders, such as Herbert Nitsch (who descended to 214 m attached to a metal sled and fixed line during the “No Limits” discipline) and Stéphane Mifsud (who achieved an 11 minutes 35 seconds breath-hold with the respiratory tract immersed in water during the “Static Apnea” discipline), achieve such remarkable performances remains, at best enigmatic.

**Landmark studies**

We reexamine published data from three unique studies detailed below:

**Mountaineers.** Arterial samples were obtained from the femoral artery of four acclimatized mountaineers at an altitude of 8400 m on Mt. Everest following descent from the summit having spent 30 minutes breathing ambient air preceded by supplementary \( \text{O}_2 \) (2–3 L/min while climbing, 0.5 L/min while sleeping above 7100 m) (Grocott et al., 2009). Individual data were available for all mountaineers in the published article. However, given that it was not possible to measure \( \text{CBF} \) at this elevation due to adverse weather, we interrogated a separate publication by the same group in a subset of five mountaineers (group not individual data available) incorporating transcranial doppler ultrasound of the right cerebral middle artery performed at the lower elevation of 7950 m, 30 minutes following removal of supplementary \( \text{O}_2 \) (Wilson et al., 2011). These are the highest elevations where such measurements have been performed.

**Freedivers.** Fifteen elite freedivers (seven having placed top 10 in the world) were examined during a static dry (laboratory-based) apnea. Individual data were made available for all freedivers (Dr. C.K. Willie, personal communication). Volumetric flow was measured continuously using near-concurrent duplex vascular ultrasound measures of blood flow through the right internal carotid and left vertebral arteries complemented by serial samples obtained from the radial artery for blood gas analysis (Willie et al., 2015a).

**Results and Discussion**

**Respiratory gas extremes and cerebral vasodilation: significance and mechanisms**

A comparison of arterial blood gas results is outlined in Table 1, including an as of yet unpublished presentation of the most hypoxemic individuals in whom the lowest \( \text{PaO}_2 \)’s (19–23 mmHg) and greatest extremes of \( \text{PaCO}_2 \) (16–61 mmHg) were recorded. Despite exhibiting the lowest \( \text{PaO}_2 \) and \( \text{SaO}_2 \), polycythemia attenuated the reduction in \( \text{CaO}_2 \) observed in the mountaineer such that the freediver was ultimately the most hypoxemic. Given that supplemental \( \text{O}_2 \) is prescribed to patients when \( \text{P}_{\text{aO}_2} \) falls <60 mmHg (consistent with the clinical diagnosis of respiratory failure) and risk of death increases exponentially <25 mmHg, combined with the increased mortality observed in hospitalized patients...
with PaCO₂’s of <35 or >45 mmHg (Laserna et al., 2012), puts their extraordinary tolerance to hitherto unchartered extremes of hypoxemia, alkalosis, and acidosis into clearer physiological perspective.

These unique datasets provide unique insight into the underlying mechanisms, notably the extent to which cerebral vasodilation likely promotes survival in such harsh environmental extremes. As illustrated in Figure 1A, this highly conserved physiological response compensates for any reduction in CaO₂ even at the physiological extremes of arterial hypoxemia, the environmental challenges to which most hypoxemic individuals respond with PaCO₂’s of <35 or >45 mmHg (Laserna et al., 2012), puts their extraordinary tolerance to hitherto unchartered extremes of hypoxemia, alkalosis, and acidosis into clearer physiological perspective.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Most hypoxemic individuals</th>
<th>Group data</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Discipline</strong></td>
<td><strong>Mountaineer (n=1)</strong></td>
<td><strong>Freediver (n=1)</strong>*</td>
</tr>
<tr>
<td><strong>Achievement</strong></td>
<td>Exposure to 8400 m</td>
<td>Apnea of 435 seconds</td>
</tr>
<tr>
<td>PaO₂ (mmHg)</td>
<td>19</td>
<td>23</td>
</tr>
<tr>
<td>PaCO₂ (mmHg)</td>
<td>16</td>
<td>61</td>
</tr>
<tr>
<td>SatO₂ (%)</td>
<td>34</td>
<td>38</td>
</tr>
<tr>
<td>Hb (g/dL)</td>
<td>18.7</td>
<td>14.5</td>
</tr>
<tr>
<td>TCO₂ (mmol/L)</td>
<td>11</td>
<td>30</td>
</tr>
<tr>
<td>CaO₂ (mL/dL)</td>
<td>9.0</td>
<td>7.6</td>
</tr>
<tr>
<td>pH (U)</td>
<td>7.45</td>
<td>7.28</td>
</tr>
<tr>
<td>Lactate (mmol/L)</td>
<td>2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Base excess (U)</td>
<td>–9.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Bicarbonate (mmol/L)</td>
<td>10.7</td>
<td>28.7</td>
</tr>
</tbody>
</table>

Freediver and mountaineer data based on publications of Willie et al. (2015a) and Grocott et al. (2009), respectively. Group data expressed as mean ± SD; PaO₂/PaCO₂, arterial partial pressure of oxygen/carbon dioxide; SaO₂, arterial oxyhemoglobin saturation; Hb, hemoglobin.

*Dr. C.K. Willie (personal communication).

**Different (p < 0.05) between disciplines assessed by independent samples t-tests following confirmation of distribution normality (Shapiro–Wilk W tests).

*Calculated from raw data: TCO₂, total carbon dioxide = [HCO₃⁻] + zPCO₂, where z = 0.226 mmol/L/kPa (kPa = mmHg × 10⁻³) and CaO₂, arterial oxygen content = So₂ × Hb × 1.39 + (PaO₂ × 0.003).

Atmosphere versus biosphere: battle of the gases

While both athletes share the common feature of severe arterial hypoxemia, the environmental challenges to which they are exposed and corresponding physiological demands are markedly different (Fig. 1A) suggesting that the mechanisms by which CDO₂ is sustained may differ between groups. Cerebral vasodilation depends on the magnitude and duration of the hypoxic stimulus, extent of acid–base adjustment, intrinsic cerebral reactivity to changes in O₂, CaO₂, pH, and systemic/local release of vasoactive metabolites (Ainslie et al., 2016). High-altitude mountaineering is characterized by long-term exposure to hypobaric hypoxia, increased BMR, hyperventilation-induced hypocapnia, respiratory alkalosis, normotension, and polycythemia, whereas freediving is characterized by short-term exposure to normobaric hypoxia during apnea, decreased BMR, hypercapnia, respiratory acidosis, and hypertension subsequent to chemoreflex activation of the sympathetic nervous system, with normal Hb concentrations. Freedivers also have to contend with the additional challenge of elevated hydrostatic pressure when competing “at depth” in select disciplines.
(e.g., 22.3 ATA during Herbert Nitsch’s No Limits world record) and complications associated with pulmonary baro-trauma, nitrogen narcosis, decompression sickness, and high pressure neurological syndrome (Lindholm and Lundgren, 2009). Indeed, it is intriguing to note that the lowest PO2's recorded in humans can arise from opposing ends of the atmospheric–biospheric pressure spectrum.

The overall CBF response to high altitude reflects the net balance of two opposing physiological stimuli, hypoxic vasodilation versus hyperventilation-induced hypocapnic vasoconstriction. Despite the brain’s increased sensitivity to PaCO2 (Kety and Schmidt, 1948a; Willie et al., 2012), the balance is tipped in favor of hypoxic vasodilation during prolonged exposure to extreme altitude reflecting the overarching drive to preserve CDO2 as illustrated in Figure 1A, B. Indeed, it is remarkable that extreme hypoxemia in the mountaineers evoked an order of magnitude more vasodilation (technical differences acknowledged) compared to the synergism expected between extreme hypoxemia, hypercapnia, and hypertension in the freediver. Indeed, it is of interest to note that despite marked differences in the environmental challenges encountered and varying PaCO2’s, the slope of the ΔCBF-CaO2 relationship for the single (most hypoxemic) freediver is identical to the average slope observed for the mountaineers during acute hypoxia.

The observed differences in acid–base balance are likely to exert opposing effects on the athletes’ respective O2-Hb dissociation curves given the inverse relationship between O2-Hb binding affinity, pH, and pCO2 (Bohr effect) (Bohr et al., 1904). Respiratory alkalosis (mountaineer) will cause a

**FIG. 1.** Relative increases in CBF (A) and oxygen delivery (CDO2; B) observed across the spectrum of reductions in arterial oxygen content (CaO2) during passive exposure to acute hypoxia lasting <24 hours (n = 84). Filled/open symbols reflect poikilocapnic/isocapnic exposure to hypoxia (10%–18% FIO2). Δcalculated as (hypoxia – normoxia) × 100 (%). Note (1) the reductions in CaO2 observed in the (individual) freediver and mountaineer described in Table 1 are the most marked recorded in the human literature to date and (2) marked hyperemia and corresponding increase in CDO2 observed in the freediver (CBF not measured in the mountaineer at the prevailing CaO2) consistent with that predicted from group mean data (identical slopes) (Kety and Schmidt, 1948b; Cohen et al., 1967; Shapiro et al., 1970; Bailey et al., 2009b; Wilson et al., 2011; Willie et al., 2012, 2015b; Ainslie et al., 2014; Hoiland et al., 2015; Sagoo et al., 2016). CBF, cerebral blood flow.
leftward (increased O$_2$-Hb affinity) facilitating greater O$_2$ uptake in the lung for any given alveolar PO$_2$, although this is likely to be countered at least to some extent by 2,3-diphosphoglycerate formation (Mairbaurl et al., 1993). In contrast, respiratory acidosis (freediver) will cause a rightward shift (decreased O$_2$-Hb affinity) favoring O$_2$ off-loading to the tissues. Evidence generally favors a leftward shift as being the most beneficial during severe hypoxia (Petschow et al., 1977) given that the slope of the O$_2$-Hb dissociation curve at the prevailing alveolar PO$_2$’s is steeper than the slope at the tissue PO$_2$’s (Turek et al., 1984) rendering Nitsch’s freediving record even more impressive. Furthermore, respiratory alkalosis blunts sympathetic tone, pulmonary vasoconstriction, and cerebral vasodilation, whereas the opposite occurs in response to hypercapnic acidosis further highlighting the complex relationship between acid–base balance and physiological responses to hypoxia (Swenson, 2016).

**Pushing the limits of hypoxemia and hyperemia**

Since the mid to late 1940s, the No-Limits freediving world record has improved by a remarkable 720% (from 30 to 216 m) compared with other sports, for example, a 6% improvement in the 100 m sprint world record observed over a similar time frame (from 10.20 to 9.58 seconds). The question thus arises as to what is the maximum depth or lowest PaO$_2$ that the healthy human can ultimately tolerate before loss of consciousness (LOC) ensues, herein referred to as the critical PaO$_2$ (PaO$_2$CRIT)? Pioneering studies reported PaO$_2$CRIT values in the range of 16–20 mmHg during instantaneous hypoxia induced by rapid decompression (1 second) or nitrogen hyperventilation (17 seconds) (Ernsting, 1963). While such challenges are clearly supraphysiological, LOC generally supervenes when the jugular venous (jv) PO$_2$ falls to ~20 mmHg (range 17–20 mmHg), which corresponds to an approximate SvO$_2$ (upper limit) of 32% (Severinghaus, 1966) and calculated CvO$_2$ of 6.8/100 mL (assuming a Hb concentration of 15 g/dL). From these figures, it is possible to approximate the PaO$_2$CRIT assuming a global (average) CBF of 46 mL/100 g/min (36–56 mL/100 g/min) equivalent to 644 mL/min (504–784 mL/min) assuming an average brain mass of 1400 g (1300–1500 g) and average CMRO$_2$ of 3.0 mL/100 g/min (2.6–3.4 mL/100 g/min) or 42 mL/min (36–48 mL/100 g/min) (Madsen et al., 1993). Using the average values cited, the CaO$_2$–CvO$_2$ can thus be derived using the Fick Principle:

\[
\text{CaO}_2\text{–CvO}_2 = \frac{\text{CMRO}_2}{\text{CBF}} = \frac{42}{644} \times 100 = 6.5 \text{ mL}/100 \text{ mL}.
\]

This equates to an (uncompensated) CaO$_2$ of 13.3/100 mL (6.8 + 6.5/100 mL) as the average minimum to avoid LOC or SaO$_2$CRIT of ~65% and PaO$_2$CRIT of ~35 mmHg, values that are far in excess of those recorded in the two most hypoxic humans documented in Table 1, suggesting that other compensatory factors, notably cerebral vasodilation (and acid–base adjustments) are contributing. In support, recalculation of the Fick Principle demonstrates that the doubling of CBF observed in the freediver has the effect of further lowering SaO$_2$CRIT to ~40% and PaO$_2$CRIT to ~23 mmHg (latter corrected for prevailing pH and base excess), almost identical to the values observed (Table 1). These values are likely to be even lower for the mountaineers given such pronounced hypoxemia, although unlikely to fall below 20 mmHg, which appears to be the lower limit observed in patients with severe respiratory disease who also exhibit polycythemia and maximal cerebral vasodilation (Refsum, 1963).

Whether prolonged exposure to extreme hypoxia in the Wilson et al. (2011) study represents maximal dilation of the cerebral vessels is unknown. It would be interesting to examine if experimental manipulation of PaCO$_2$ would incur further increases given the ~5.5% increase in CBF per mmHg increase in PaCO$_2$ reported during iso-oxic end-tidal forcing (Willie et al., 2012). However, the CBF response at physiological extremes of hypoxia–hypercapnea is not a simple summative dose–response. Emerging evidence suggests that severe hypoxia blunts the normal cerebrovascular reactivity to CO$_2$ possibly due to exhaustion of the cerebral vasodilatory reserve (Fan and Kayser, 2013) or alternatively, to protect against severe blood–brain barrier disruption and complications associated with extracellular vasogenic cerebral edema (Bailey et al., 2009c).

Notwithstanding the uncertainties associated with acid–base adjustments and corresponding shifts in the O$_2$-Hb dissociation curve as outlined, these calculations are at the very least hypothesis testing and demonstrate that these athletes are operating very close to, if not indeed at, the very limit of human consciousness, findings corroborated by the high incidence of LOC and loss of motor control (confusion, loss of postural control, faltering vision, speech problems) recorded among competitive freedivers, clinical signs that are the frustrating cause for disqualification. Furthermore, emerging MRI and immunochemical evidence suggests that extremes of freediving and high-altitude mountaineering may be associated with structural brain damage (Bailey et al., 2009a; Gren et al., 2016) with potential long-term neuropsychological consequences. This contrasts with the extraordinary hypoxia tolerance exhibited by diving mammals, including the seal that is capable of enduring PaO$_2$’s as low as 7–10 mmHg without cerebral integrity being compromised (Elsner et al., 1970).

While global CDO$_2$ in humans may appear well preserved both at rest and even during maximal exercise in hypoxia, the overall reduction in jv (Ainslie et al., 2014) and (derived) cerebral mitochondrial PO$_2$ (Bailey et al., 2011) reported in the literature suggests that it is heterogeneous and regional PO$_2$ deficits likely coexist, which has important implications for regional susceptibility to damage or indeed adaptation. Regional differences in the CBF, and hence CDO$_2$ response to hypoxia, have since been observed, complicated in part by differing analytical techniques, experimental designs, and fact that the entire cerebral arterial tree including large arteries of the neck exhibit differential reactivities to PaO$_2$ and PaCO$_2$ (Willie et al., 2014). Increased CBF reactivity has been reported in the putamen, brain stem, thalamus, caudate nucleus, nucleus accumbens, and pallidum using H$_2^{15}$O positron emission tomography (Binks et al., 2008), whereas single photon emission computed tomography has identified predeletion for the anterior cingulate cortex, right temporal lobe, sensory motor cortices, prefrontal cortex, and basal ganglia (Pagni et al., 2011). Collectively, these findings have been taken to reflect the selective preservation of CDO$_2$ to phylogenetically older regions of the brain responsible for more vital aspects of homeostatic function, a feature that may have provided a selective advantage.
Conclusion

A reexamination of published data from freedivers and mountaineers, extreme athletes in whom the lowest PaO₂'s and greatest extremes of PaCO₂ to date have been recorded, highlights to what extent compensatory increases in CBF are sufficient to preserve CDO₂ consistent with the conservation of mass principle. While the molecular mechanisms underlying O₂-CO₂ sensing remain elusive, cerebral vasodilation likely contributes toward these athletes' extraordinary abilities to survive in such harsh environments characterized by physiological extremes of hypoxemia, alkalosis, and acidosis helping define the human brain’s remarkable limits of tolerance.

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Authors’ Contributions

D.M.B. drafted the article and revisions thereof; coauthors approved the final article for submission.

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