Exercise-induced arterial hypoxemia

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Dempsey, Jerome A., and Peter D. Wagner. Exercise-induced arterial hypoxemia. J. Appl. Physiol. 87(6): 1997–2006, 1999.—Exercise-induced arterial hypoxemia (EIAH) at or near sea level is now recognized to occur in a significant number of fit, healthy subjects of both genders and of varying ages. Our review aims to define EIAH and to critically analyze what we currently understand, and do not understand, about its underlying mechanisms and its consequences to exercise performance. Based on the effects on maximal O2 uptake of preventing EIAH, we suggest that mild EIAH be defined as an arterial O2 saturation of 93–95% (or 3–4% <rest), moderate EIAH as 88–93%, and severe EIAH as <88%. Both an excessive alveolar-to-arterial PO2 difference (A-aDO2) (>25–30 Torr) and inadequate compensatory hyperventilation (arterial PCO2 >35 Torr) commonly contribute to EIAH, as do acid- and temperature-induced shifts in O2 dissociation at any given arterial PO2. In turn, expiratory flow limitation presents a significant mechanical constraint to exercise hyperpnea, whereas ventilation-perfusion ratio maldistribution and diffusion limitation contribute about equally to the excessive A-aDO2. Exactly how diffusion limitation is incurred or how ventilation-perfusion ratio becomes maldistributed with heavy exercise remains unknown and controversial. Hypotheses linked to extravascular lung water accumulation or inflammatory changes in the “silent” zone of the lung’s peripheral airways are in the early stages of exploration. Indirect evidence suggests that an inadequate hyperventilatory response is attributable to feedback inhibition triggered by mechanical constraints and/or reduced sensitivity to existing stimuli; but these mechanisms cannot be verified without a sensitive measure of central neural respiratory motor output. Finally, EIAH has detrimental effects on maximal O2 uptake, but we have not yet determined the cause or even precisely identified which organ system, involved directly or indirectly with O2 transport to muscle, is responsible for this limitation.

characterizing EIAH

Exercise-induced arterial hypoxemia definition; excessive alveolar-to-arterial PO2 difference; ventilation-perfusion ratio maldistribution; hyperventilatory compensation; maximal oxygen uptake limitation; airway inflammation

THE PROBLEM OF THE LUNGS’ CAPABILITY for maintaining homeostasis of arterial blood O2 content and acid-base status during exercise is long-standing in physiology, dating back to before the turn of the 20th century. In the past decade or two, with the development of new approaches to assessing ventilation and perfusion distribution in the lung and with the growing number of observations indicating that gas exchange is far from perfect in the exercising healthy lung, research interest in this problem has intensified. Scientists specializing in respiratory, comparative, environmental, and exercise physiology and in neurophysiology have all been attracted to some aspect of this multifaceted problem, which speaks not only to the intricacies of gas exchange in the lung but also to the neural, chemical, and mechanical determinants of ventilation and to the broader problem of limitations to exercise performance. Our brief synopsis of this problem attempts first to characterize and also to define exercise-induced arterial hypoxemia (EIAH) in humans and other mammals and then to critically analyze the underlying mechanisms of EIAH and its consequences to maximal O2 uptake (VO2max) and exercise performance.

CHARACTERIZING EIAH

The level of oxygenation in arterial blood during exercise is defined by measurements of PO2, HbO2
saturation, and O2 content. Arterial Po2 (PaO2) is determined by the level of alveolar ventilation at any given metabolic demand, together with the efficiency with which O2 is exchanged between alveolar gas and arterial blood, as indicated by the alveolar-to-arterial Po2 difference (A-aDO2). Arterial O2 saturation (SaO2) follows PaO2 but may be modified by O2 dissociation curve shifts caused by changes in pH, PCO2, and blood temperature. Arterial O2 content (CaO2) follows saturation but will be modified by Hb concentration, which generally increases slightly from rest to heavy exercise. Sufficient data are available over the past half century to define typical changes in these indexes of oxygenation in the young, healthy, habitually inactive or mildly active adult men with V˙O2max in the 35–55 ml·kg⁻¹·min⁻¹ range. This response typically consists of a gradual widening of the A-aDO2 from rest (5–10 Torr) to maximal exercise (20–25 Torr), accompanied by a ventilatory response that rises out of proportion to increasing O2 uptake (V˙O2) and CO2 production (V˙CO2) in moderately heavy through maximum exercise, thereby raising alveolar Po2 [and reducing arterial PCO2 (PaCO2)] sufficiently to prevent arterial hypoxemia. As highly fit young adult men, and then women and the elderly, were tested in larger numbers beginning in the 1960s, several instances of EIAH have been reported, whereby occasionally PaO2 is reduced by as much as 30 Torr and SaO2 by as much as 15% below resting levels. We consider it adequately documented that significant EIAH does occur in a significant number of healthy, fit subjects during exercise near sea level (e.g., Refs. 7, 10, 21, 22, 42, 47).

Defining EIAH and Its Components

We propose simple guidelines for defining a significant EIAH, which address two specific purposes: 1) to identify a significant threat to systemic O2 transport; and 2) to quantify abnormalities in each of the two key determinants of PaO2, namely, the ventilatory response and the efficiency of alveolar-to-arterial gas exchange. The choice of EIAH definition will depend on the research question one wishes to address. In this review, we consider EIAH broadly as reduced arterial oxygenation, which may result from a fall in PaO2 (and thus also in SaO2), from a rightward shift of the O2 dissociation curve without a fall in PaO2 or from a combination of these processes.

EIAH as a threat to O2 transport. Reductions in SaO2 (and, therefore, in CaO2), rather than in PaO2, better define the consequences of EIAH to systemic O2 transport and to V˙O2max. As discussed in detail below (see CONSEQUENCES OF EIAH), preventing EIAH by using supplementary inspired O2 increases V˙O2max in many subjects (13, 23, 41, 55). The measurable threshold of this effect occurs at a ~3% reduction in SaO2, from a normal resting value of 98%, and a linear association between ΔSaO2 and ΔV˙O2max (where Δ indicates change) is observed beyond this threshold range such that each further 1% reduction in SaO2 (or CaO2) causes a ~1–2% reduction in V˙O2max. Accordingly (until the study of larger groups determines otherwise), we suggest that EIAH be defined so that mild EIAH would correspond to an absolute SaO2 of 93–95%; moderate EIAH to an absolute SaO2 in the range of 88–93%; and severe EIAH to SaO2 values <88%. It is important to keep in mind that SaO2 may be reduced in heavy exercise, not only because of reductions in PaO2 but also (and often to an equal extent) by a pH- and temperature-induced rightward shift of the HbO2 dissociation curve (see Figs. 1 and 2). It is advisable then to distinguish (and to report) the independent effects of a reduced PaO2 vs. pH and

Fig. 1. Exercise-induced hypoxemia in Thoroughbred horses (see Refs. 55, 57). A: essentially sequential fall in arterial Po2 (PaO2) and then arterial O2 saturation (SaO2; satur) from rest to gallop. Note large drop in saturation caused by rightward movement of the O2 dissociation (diss) curve at heavy exercise. B: SaO2 and O2 uptake (V˙O2) from walk to maximal gallop in the same horses. Data for 3 inspiratory O2 fractions (FIO2) are shown, exemplifying not only sensitivity of SaO2 to both exercise and FIO2 but also dependence of maximal V˙O2 (V˙O2max) on SaO2.
temperature effects on $\text{Sa}_2$ by using a standardized HbO2 dissociation curve.\(^1\)

EIAH as an indicator of inadequacies in ventilation and gas exchange. It is also important to identify and quantify the key components of abnormal gas exchange, as defined by excessive widening of $A-a\text{DO}_2$ and/or insufficient alveolar hyperventilation during exercise. Essentially, all normal subjects develop an increased $A-a\text{DO}_2$ with exercise, and values of 15–25 Torr are common at $V\dot{O}_2_{max}$. Arterial $P\text{CO}_2$ usually falls to 30–35 Torr. Based on such responses, we suggest that an $A-a\text{DO}_2$ in the 25–30 Torr range is excessive and that if $A-a\text{DO}_2$ exceeds 35–40 Torr, severe inefficiencies in gas exchange are present. Correspondingly, $P\text{aCO}_2$ in the 35–38 Torr range indicates a borderline effective alveolar hyperventilation, and $P\text{aCO}_2 > 38$ Torr suggests the absence of a compensatory hyperventilatory response. The use of these criteria may serve as a guide in identifying the key potential determinants of EIAH; however, it is important to recognize that one of these two criteria may be abnormal during exercise without actually resulting in significant reductions in $P\text{aO}_2$ or $\text{Sa}_2$ underlining the need to separately consider EIAH in terms of its effects on $O_2$ transport and its relationship to pulmonary gas exchange and ventilation.

Relationship of EIAH to $V\dot{O}_2_{max}$ and Habitual Activity Levels

Habitually active subjects are the only healthy subjects thus far to demonstrate EIAH in appreciable numbers. The correlation of EIAH to $V\dot{O}_2_{max}$ is usually significant within the various groups studied; however, there are also several instances of weak correlations of EIAH vs. $V\dot{O}_2_{max}$ and of subjects (e.g., women) with $V\dot{O}_2_{max}$ within 20% of normal predicted values who experienced significant EIAH. Equally impressive and mysterious are the large numbers of highly fit male and female endurance athletes of all ages ($V\dot{O}_2_{max}$ 150–200% of predicted normal), who do not experience significant EIAH, even at their very high peak work rates (7, 14, 21, 42, 50).

Prevalence of EIAH. The prevalence of EIAH near sea level has been estimated at ~50% of young, adult, highly fit male athletes (40), but this estimate is at best a guess, because insufficient numbers of subjects have been tested by using direct measurements of arterial blood gases. Furthermore, the prevalence of EIAH will likely vary with such factors as age and gender, and certainly the numbers studied to date within each of these basic categories are woefully small.

EIAH and Exercise Intensity

When EIAH is present, it usually peaks at or near maximal exercise intensity. In many cases, a consistent fall in $P\text{aO}_2$ is not obvious until very heavy or maximum exercise. On the other hand, in many trained subjects, the trend toward EIAH clearly begins at moderate intensity workloads, as $A-a\text{DO}_2$ widens with little or no accompanying hyperventilatory compensation (7, 14, 46). In such subjects, as exercise intensity further increases, $P\text{aO}_2$ and $\text{Sa}_2$ continue to fall as $A-a\text{DO}_2$ widens further, compensatory hyperventilation is minimal, and metabolic acidosis ensues. This ten-
tendency toward developing EIAH in submaximal exercise has not been emphasized sufficiently in studies to date. Its occurrence may have significant implications for deciphering the causes of EIAH (see below).

The mode and duration of exercise. The mode and duration of exercise will affect EIAH. EIAH commonly occurs only transiently with very brief progressive exercise because of ventilatory lag, and then \( P_{A\text{O}_2} \) increases over time with increasing ventilation. On the other hand, in fit subjects susceptible to EIAH who undergo 4–5 min of heavy-intensity, constant-load exercise, \( P_{A\text{O}_2} \) falls within the initial 30–60 s of exercise and is maintained at this reduced level throughout the ensuing 3–4 min (7). Even if \( P_{A\text{O}_2} \) stays level, \( S_{A\text{O}_2} \) may continue to fall further as pH falls. The general impression is that treadmill running and walking cause greater and more consistent EIAH than does cycle ergometry, in part because of a greater ventilatory response to cycling. However, there is also evidence of a greater degree, but \( P_{A\text{O}_2} \) is maintained near resting values. The general impression that treadmills running and walking cause greater and more consistent EIAH than does cycle ergometry, in part because of a greater ventilatory response to cycling. However, there is also evidence of a greater degree (53), accounting for the higher specific \( V_{O_2\text{max}} \) in smaller species, data show changes generally similar to those in humans. Whereas less athletic species (goat, calf, rat) show little gas-exchange inefficiency at peak exercise, highly athletic species (dog, horse) develop a large A-aDO2 at maximal effort. Just as for humans, the degree of hyperventilation during exercise is variable, and, as a result, \( P_{A\text{O}_2} \) and \( P_{A\text{CO}_2} \) change in ways reflecting both the ventilatory response and the gas-exchange inefficiencies.

Table 1 shows typical data from a number of animal studies and indicates the range of responses. It is evident that, except for the Thoroughbred racehorse (55), \( P_{A\text{CO}_2} \) is reduced by hyperventilation during exercise. In the goat, calf (52), and rat (9), the A-aDO2 is slightly excessive, but their considerable hyperventilation keeps \( P_{A\text{O}_2} \) high. In more aerobic species, e.g., pig (18), dog (20), and fox (30), A-aDO2 begins to rise to a greater degree, but \( P_{A\text{O}_2} \) is maintained near resting levels by hyperventilation. In still more athletic animals (pony (52)), \( P_{A\text{O}_2} \) cannot be maintained despite hyperventilation. Finally, in the trained Thoroughbred horse (55), A-aDO2 is high, alveolar hypoventilation occurs, and there is considerable EIAH. The horse thus represents an extreme, which may reflect selective breeding by humans that has focused on enhancing cardiovascular and not pulmonary function. Interpretation of these data is facilitated by noting that \( V_{O_2\text{max}} \) scales to body size (log/log plot) with a slope of only 0.81 (53), accounting for the higher specific \( V_{O_2\text{max}} \) in smaller animals. Species that can reach a \( V_{O_2\text{max}} \) greater than expected from Taylor's scaling relationship (horse and

<table>
<thead>
<tr>
<th>Species</th>
<th>Ref. No.</th>
<th>( P_{O_2} ), Torr</th>
<th>( P_{CO_2} ), Torr</th>
<th>A-aDO2, Torr</th>
<th>( S_{A\text{O}_2} ), %</th>
<th>( V_{O_2\text{max}} ), ml·kg(^{-1})·min(^{-1})</th>
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<tr>
<td>Goat</td>
<td>52</td>
<td>105</td>
<td>37</td>
<td>2</td>
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<tr>
<td>Calf</td>
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<td>108</td>
<td>39</td>
<td>0</td>
<td>100.0</td>
<td>37</td>
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<tr>
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<td>9</td>
<td>96</td>
<td>36</td>
<td>14</td>
<td>93.9</td>
<td>74</td>
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<td>104</td>
<td>43</td>
<td>0</td>
<td>89.7</td>
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<td>105</td>
<td>41</td>
<td>4</td>
<td>81.6</td>
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A-aDO2, alveolar-to-arterial \( P_{O_2} \) difference; \( S_{A\text{O}_2} \), arterial \( O_2 \) saturation; \( V_{O_2\text{max}} \), maximal \( O_2 \) uptake.
dog) are those with the greatest inefficiencies in pulmonary gas exchange.

**CAUSES OF EIAH**

In humans, EIAH severity correlates most consistently and inversely with A-aDO₂. Interindividual differences in PaCO₂ or the ventilatory equivalent for VO₂ (or VCO₂) are also commonly found to correlate significantly with EIAH; however, there are many exceptions, especially in mild EIAH, and thus the degree of hyperventilation accounts for less of the variance in PaO₂ in most studies. Those men and women, in both young and old age groups, who experience severe EIAH have almost equal contributions from the absence of hyperpnea, with an appreciation of the multiple factors that determine the level of ventilatory stimuli (including circulating hormonal stimuli) and that explain the ventilatory response to heavy exercise. First, with an appreciation of the multiple factors that determine exercise are best predicted from a multiple linear-regression model (r = 0.93)², where ventilation (as reflected by PaCO₂) explains ∼60% of the variance in SaO₂, VO₂max accounts for 25% of it, and A-aDO₂ for the remainder.

Why Inadequate Hyperventilatory Compensation?

The answer to this question is complex and begins with an appreciation of the multiple factors that determine the ventilatory response to heavy exercise. First, the level of ventilatory stimuli (including circulating H⁺ concentration, K⁺ concentration, O₂, and catecholamines plus powerful neural feedforward and feedback influences) is an important consideration. However, stimulus levels are, if anything, greater in subjects with EIAH and, therefore, could not explain the accompanying inadequate hyperventilatory response. Second, the mechanical influences of airway diameter and respiratory muscle force production may prevent expression of the full ventilatory response to existing stimuli. Evidence favoring a role for mechanical constraint includes observations that the gains of the ventilatory and tidal volume (Vₜ) responses to added chemoreceptor stimuli are reduced during heavy and maximal workloads relative to those obtained during mild and moderate exercise intensities (5, 22, 32, 33). A third factor, often invoked to explain differences in ventilatory responses to exercise, is the interindividual difference in sensitivity to both existing stimuli and to mechanical constraints.

Much of the mechanical constraint on minute ventilation (Vₑ) appears to be imposed by the airways that have an upper limit to flow rate, especially on expiration, as defined by the maximum volitional flow-volume envelope. Partial encroachment of the VT on the maximum flow-volume envelope is experienced by most trained subjects during heavy to maximum exercise. In many very fit young men, and especially in women and older fit adults, almost all of the flow-volume envelope may be utilized during maximal exercise (21, 22, 31). These groups are especially vulnerable to expiratory flow limitation during maximum exercise because of their high metabolic rate, and therefore, ventilatory requirements, combined with 1) a normal maximum flow-volume envelope in the young men; 2) a smaller envelope in the women (relative to men of similar height); and 3) a substantial age-dependent reduction in lung elastic recoil and expiratory flow reserve in the 65- to 75-year-old endurance athletes. That this flow limitation may constrain Vₑ is demonstrable experimentally by the increase in VT and Vₑ and to eliminate expiratory flow limitation (32). These data also suggest that <50% of the VT needs to encroach on the maximum expiratory flow-volume envelope to cause EELV to rise and VT and Vₑ to be constrained. Perhaps then even minimal amounts of expiratory flow limitation may initiate, reflexively, termination of expiratory effort; as EELV increases, inspiratory motor output would be inhibited via increased vagal feedback from lung stretch at high end-inspiratory lung volume (2, 38). However, this is speculation. We do not even know if a true reflex inhibition actually occurs with the onset of (impending) flow limitation. Valid, artifact-free methods for measuring central neural respiratory motor output in the exercising human are needed so that we can even begin to understand ventilatory control during heavy-intensity exercise.

Another potential mechanical limit to Vₑ is the pressure or force developed by inspiratory muscles, which may approach 90% of their capacity at peak exercise in fit subjects (22, 29). However, when a proportional-assist ventilator was used to unload the inspiratory muscles under these conditions, changes in Vₑ were variable and often insignificant, indicating either that the respiratory muscle load, per se, was not an important constraint to Vₑ or that behavioral responses to positive-pressure mechanical ventilation became a dominant factor in controlling Vₑ during exercise (27).

An important but poorly understood factor determining the ventilatory response to heavy exercise is the marked interindividual differences in ventilatory responsiveness or receptor sensitivity, either to the available neurohumoral stimuli or to the inhibitory feedback.  

² SaO₂ (%) = 110.4 − 0.38·PaCO₂ − 0.80·A-aDO₂ − 0.51·VO₂max/kg.

³ The proximity of the tidal to the maximum flow-volume envelope during exercise correlates with simultaneous measures of the proximity of tidal expiratory pressures to maximum effective transpulmonary pressure (Pmax) (21, 37). However, in most instances, truly maximum effective flow and pressure are only achieved over a portion of the VT at low lung volumes. Thus "complete" flow limitation is usually not achieved in the sense that further imposed changes in transpulmonary pressure would not increase expiratory flow rate over some lung volumes (34).
influences from mechanoreceptors. For example, there
are subjects who show a sluggish ventilatory response
to heavy exercise with little or no obvious mechanical
constraint via flow limitation (21, 22). On the other end
of the spectrum are those subjects who show significant
expiratory flow limitation but continue to increase their
respiratory motor output and ventilation right to the
very limits of their flow-volume envelope, despite the
production of extremely negative inspiratory and posi-
tive expiratory pleural pressures. Furthermore, several
subjects with EIAH will underventilate during even
mild and moderate exercise intensity, i.e., in the ab-
sence of significant flow limitation or of high loads on
the respiratory muscles (7, 14, 15, 28, 46). So, blunted
stimulus responsiveness likely contributes signifi-
cantly to the reduced ventilatory response to exercise.
Unfortunately, these characteristics are not consist-
tently predictable from conventional (resting) hypoxic
or hypercapnic ventilatory response tests, and the
popular generalization that highly trained endurance
athletes all have blunted chemoreceptor responses has
many exceptions.

We emphasize that EIAH is not completely prevent-
able by improving VA, at least within realistic limits.
For example, in very fit subjects with the most severe
EIAH and with A-aDO2 > 35 Torr, PaCO2, in the 36–39
Torr range, and VE at 85% of ventilatory capacity,
it may be predicted (by using the alveolar air equation)
that VE would need to increase by > 50 l/min or by
35–50% and PaCO2 to fall below 25 Torr to maintain
PaO2 > 85 Torr at VO2max. Interestingly, similar in-
creases in VA would be required to drive PaCO2 low
enough so as to completely compensate arterial pH in
the face of the accompanying metabolic acidosis. This
degree of hyperventilation is not possible mechanically,
because these ventilatory requirements far surpass the
maximum ventilatory capacity—as estimated from the
maximum voluntary ventilation or from the maximum
flow-volume loop and breathing frequency at maximal
exercise. Experimentally, removal of expiratory flow
limitation via He–O2 breathing resulted in only a
15–20% increase in VE, a reduction in PaCO2 of 5–7 Torr,
and preventing of 30–40% of the EIAH (7, 31, 32).

Why an Increase in A–aDO2 with Exercise?

The classically described causes of an increased
A–aDO2 include 1) ventilation-perfusion (VA/Q)
inequality; 2) failure of alveolar-end capillary diffusion equili-
brium; and 3) right-to-left shunt. Shunts may occur 1)
within the lungs or between atria, ventricles, or great
vessels; and 2) in a postpulmonary setting, due to
venous admixture of arterial blood with blood from
bronchial and thebesian veins. Determining which of
these alone or in combination are responsible for any
increase in A–aDO2 with exercise is difficult, and most
such information has come from using the multiple
inert-gas-elimination technique (MIGET).

At rest, it is clear that the entire A–aDO2 is accounted
for by VA/Q inequality in normal subjects (humans and
other mammals). There is no evidence for diffusion
limitation or measurable contributions from intrapul-
monary or extrapulmonary shunts (56).

During heavy exercise, VA/Q inequality still accounts
for much, and sometimes all, of the A–aDO2, at least at
sea level (56). It is of considerable interest that the
severity of VA/Q mismatching is greater during heavy
exercise than at rest (8, 56), but the effect of this
increase in inequality on PaO2 is mitigated by the well-
known increase in overall lung VA/Q ratio. Thus,
because alveolar ventilation increases relatively more
than does cardiac output (Q) during exercise, the VA/Q
distribution is shifted to a higher range of VA/Q ratios,
thereby raising alveolar and thus arterial PaO2. Conse-
sequently, the magnitude of the A–aDO2 component attrib-
utable to VA/Q inequality remains essentially constant
from rest to exercise (56). Why VA/Q mismatch in-
creases with exercise is addressed below.

At or near VO2max, diffusion limitation appears to
develop. Whereas this is not uniformly observed, it is
more common in subjects with greater levels of fitness
and in athletic species such as horse and dog (20, 55).
Application of the MIGET is the clearest way of detect-
ing the presence of diffusion limitation, since the inert
gases used in the method are invulnerable to variable
degrees of diffusion limitation. They can, therefore,
be used to predict the PaO2 that would be expected if only
VA/Q inequality and intrapulmonary shunts existed. If
this prediction statistically matches measured values
for PaO2, one concludes that there is no diffusion
limitation present. On the other hand, diffusion limita-
tion would lead to a lower value for actual PaO2 than
predicted by MIGET (11), whether or not VA/Q inequality
and/or shunts were also present. Whereas this
difference in PaO2 is usually attributed to diffusion
limitation, it is true that bronchial and thebesian
venous admixture would lead to a similar difference
between the measured and MIGET-predicted PaO2, and
this cannot be strictly separated from diffusion limita-
tion. The magnitude of the postpulmonary shunt in
exercising humans is not known precisely. During
exercise in normoxia, a shunt as small as 1–2% of the
cardiac output may account for a substantial portion of
the difference between predicted and measured A–aDO2
(8), whereas in hypoxia unreasonably high amounts of
shunt in the range of 10–20% of the cardiac output are
required to account for the predicted to measured
A–aDO2 (36).

Significant intrapulmonary shunts cannot be identi-
fied in the majority of cases, either at rest or during
exercise, in normal subjects or animals. Even when
present, they usually amount to < 1% of the Q and have
little impact on PaO2.

There is some evidence that incomplete gas mixing
in the alveoli or airways confers a small degree of
gas-exchange inefficiency. This may cause PaO2 to fall
perhaps 12 Torr (16). Again, this is, by and large, an
essentially negligible factor in arterial oxygenation,
and there is little evidence for this in humans.

Finally, no matter what the physiological basis may
be for an increased A–aDO2, the reduction in mixed
venous PO2 that normally accompanies exercise acts to
further lower PaO2. Mixed venous PO2 falls because
\( \dot{V}O_2 \) increases relatively more than \( \dot{Q} \) from rest to exercise. The effect is to cause more diffusion limitation and also to reduce end-capillary \( P_2 \) in regions of the lung where low \( V_A/Q \) ratios exist (59). Because mixed venous \( P_2 \) commonly drops from \( \sim 40 \) Torr at rest to 20 Torr during heavy exercise, the effect is considerable.

In summary, both diffusion limitation and greater \( V_A/Q \) mismatch contribute to the increased \( A-aDO_2 \) during exercise. The contribution of \( V_A/Q \) inequality to the \( A-aDO_2 \) is generally constant from rest to \( \dot{V}O_{2\text{max}} \), whereas that of diffusion limitation is not seen until heavy or even maximal exercise is undertaken. Current data suggest that, on average, these two processes contribute similarly to the \( A-aDO_2 \) at or near \( \dot{V}O_{2\text{max}} \) (52). The reduced mixed venous \( P_2 \) further reduces \( P_{O_2,v} \), but both intrapulmonary and extrapulmonary shunts appear to be negligible.

Mechanism of Increase in \( V_A/Q \) Inequality With Exercise

Why \( V_A/Q \) mismatch worsens remains an unresolved issue. There are several candidate mechanisms: 1) normal minor structural differences in airways and/or blood vessels throughout the lungs that would cause no significant variation in airways or vascular resistance at rest could become significant on exercise because of the increase in gas and blood flow rates; 2) bronchoconstriction, even at subclinical levels, could alter ventilation distribution; 3) secretions from airways irritated by high air flow rates of sometimes cold, dry air could affect ventilation distribution; 4) modulators of airway and vascular tone in the lung could be affected, in turn altering ventilation or blood flow distribution; 5) mild interstitial edema could develop and, through changes in local compliance (alveolar wall edema) or resistance (perivascular or bronchial edema), affect the distribution of ventilation or blood flow. Of these candidates, 1 cannot be currently excluded, and direct evidence is impossible to obtain. However, the persistence of \( V_A/Q \) mismatch beyond the time required for ventilation and \( Q \) to return to resting levels postexercise (50) does not support this mechanism; 2 is not the explanation for the majority of subjects, i.e., those who do not suffer from exercise-induced bronchoconstriction; 3 also cannot be positively excluded at the present time, nor can 4. Indeed, there are data suggesting a role for histamine in the development of EIAH (44). However, there is a body of largely indirect evidence that supports the development of transient interstitial edema (1, 3, 44, 45). The problem is clearly yet unresolved.

Mechanism of Increase in Diffusion Limitation With Exercise

The degree of diffusion limitation expected in any given lung is elegantly explained by Phiper and Scheid (39) in terms of their compound variable \( D/(\beta Q) \), where \( D \) is lung diffusing capacity and \( \beta \) is the mean slope of the conceptually linear \( O_2-Hb \) dissociation curve in the physiological range. With \( D \) in \( \text{ml min}^{-1} \cdot \text{Torr}^{-1} \), \( \beta \) in \( \text{ml O}_2 \cdot \text{l blood}^{-1} \cdot \text{Torr}^{-1} \), and \( Q \) in \( \text{l min} \), when \( D/(\beta Q) \) is 4.6, diffusion equilibration would be 99% complete; \( D/(\beta Q) = 3.0 \) allows 95% equilibration; and \( D/(\beta Q) = 1.0 \) allows only 63% equilibration. Whereas all three components \((D, \beta, \text{and } Q) \) increase on exercise, \( D/(\beta Q) \) falls. This fall can be accentuated by limited gains in overall \( D \) (possibly from \( V_A/Q \) mismatching or from alveolar interstitial edema) or by greater than average increases in \( \beta \) and \( Q \). Athletes typically exhibit a high \( Q \) and also high \( O_2 \) extraction from blood perfusing muscles. Because high \( O_2 \) extraction increases \( \beta \) by increasing the average slope of the \( O_2-Hb \) curve in the working range, athletes in particular are subject to greater reduction in \( D/(\beta Q) \) than are sedentary subjects. Consequently, it is no surprise that, as discussed earlier, the most athletic subjects and species are those most subject to diffusion limitation, particularly due to high \( Q \). Recent evidence suggests that subjects with more exercise-induced hypoxemia at a given \( V_{CO_2} \) also have a lower \( D \) (47). Thus diffusion limitation is dictated by the summed effects of an intrinsically low \( D \), potentially limited increases in \( D \) with exercise, high \( O_2 \) extraction, and high \( Q \) because of training state or intrinsic athleticism.

Demand vs. Capacity as an Explanation for EIAH?

Does EIAH occur because the highly trained human or animal has undergone adaptation in nonpulmonary (i.e., cardiovascular and metabolic) determinants of maximum \( O_2 \) transport and \( \dot{V}O_{2\text{max}} \), but not at the level of the lung and airways (6)? On the one hand, this idea seems reasonable because of many findings showing that—with few exceptions—the lung in physically trained humans or in athletic animals differs not at all or very little from the sedentary animal; and that physical training sufficient to increase \( \dot{V}O_{2\text{max}} \) has no measurable effects on lung function or structure. On the other hand, evidence against this concept as the sole explanation for EIAH are some reports that the onset of excessive widening of the \( A-aDO_2 \) and, therefore, EIAH can be shown to occur in many cases, even in submaximal exercise, (see Figs. 1 and 2) and in rare cases EIAH can be equally severe in submaximal and maximal exercise (7, 14, 46). The occurrence of EIAH in submaximal exercise has not received sufficient emphasis. It may have significant implications for how we view EIAH as predominantly a result of an “underbuilt” lung in athletes, relative only to their extraordinary demand for maximum \( O_2 \) transport or whether in some cases the stresses associated with training may actually have effects on structural or secretory characteristics in the lung’s parenchyma and peripheral airways that would predispose to an excessive maldistribution of \( V_A \) and/or \( Q \) during exercise.

CONSEQUENCES OF EIAH

EIAH Effects on \( \dot{V}O_{2\text{max}} \)

The effect of EIAH on \( \dot{V}O_{2\text{max}} \) has been demonstrated in a limited number of studies in fit humans and horses by adding sufficient \( O_2 \) to the inspired air to prevent the EIAH (13, 23, 41, 55) (see Figs. 1 and 2). Note that this approach, which aims to maintain \( Sa_o \) and \( Ca_o \) at resting levels, differs substantially from the more common use of much higher concentrations of inspiratory
Critical dependence of V\(_{\text{O}2}\)\(_{\text{max}}\) on O\(_2\) transport may only be mediated via increased inspireatory CO fraction or reduced F\(_{\text{I}}\text{O}_2\) (19, 28, 57). The further reduction of V\(_{\text{O}2}\)\(_{\text{max}}\) beyond this threshold of desaturation changes linearly with SaO2 (and CaO2) such that V\(_{\text{O}2}\)\(_{\text{max}}\) is affected by 3–4% O\(_2\) desaturation below resting levels. These threshold values are similar to those found when arterial hypoxemia was caused experimentally among subjects, but a consistent effect appears to be initiated at 80% SaO2, or below (Fig. 1), and up to 15% in the human, who desaturates to a maximum of 85–90% SaO2 at V\(_{\text{O}2}\)\(_{\text{max}}\) (see Fig. 2). The majority of the effect of preventing EIAH on V\(_{\text{O}2}\)\(_{\text{max}}\) occurs because V\(_2\) is increased at a given high-intensity work rate. Thus, preventing EIAH removes the plateau effect of V\(_2\) vs. work rate and delay it until a higher work rate is reached (see Figs. 1 and 2). These data add to the substantial findings already available that have documented that O\(_2\) transport to the working tissue, as determined by blood flow, CaO2, and O\(_2\) extraction, is the important limiting factor to V\(_{\text{O}2}\)\(_{\text{max}}\) in healthy subjects, as opposed to the metabolic capacity of the muscle mitochondria (see Ref. 57 for review). This critical dependence of V\(_{\text{O}2}\)\(_{\text{max}}\) on O\(_2\) transport may only apply to normal or highly trained subjects, whereas the V\(_{\text{O}2}\)\(_{\text{max}}\) in the extremely sedentary subject or animal may not be O\(_2\) supply dependent (4, 23).

EIAH becomes an especially important determinant of V\(_{\text{O}2}\)\(_{\text{max}}\) in hypoxic environments, particularly in the highly trained athlete, who usually suffers the greatest decrement in V\(_{\text{O}2}\)\(_{\text{max}}\) at high altitudes (10, 28). Thus even relatively small decrements in inspired P\(_{\text{O}}2\) (for example to 120–130 Torr or ~1,000 m altitude), which would not be expected to influence SaO2 or V\(_{\text{O}2}\)\(_{\text{max}}\) appreciably in the untrained, have been shown to precipitate substantial EIAH at the high work rates achieved in the highly fit, with marked decrements in V\(_{\text{O}2}\)\(_{\text{max}}\) and endurance exercise performance. Even trained subjects with mild or even no discernible EIAH at sea level may experience moderate to severe EIAH in the face of only modest decrements in inspiratory P\(_{\text{O}}2\) (7, 10). Diffusion limitation at these high work rates in hypoxic environments is a likely cause of EIAH in the athlete (see above), along with limited room within the maximum flow-volume envelope to further increase alveolar ventilation in response to hypoxic chemoreceptor stimulation during heavy exercise (22).

Mechanisms of EIAH Effects on V\(_{\text{O}2}\)\(_{\text{max}}\)

The effect of EIAH on V\(_{\text{O}2}\)\(_{\text{max}}\) is fairly predictable based solely on the reduction in SaO2 and CaO2 and therefore, in turn, on the limits placed on the widening of the maximal arterial-to-venous O\(_2\) content difference across the working muscle. This change in the maximal arterial-to-venous O\(_2\) difference in proportion to the change in CaO2 has not been documented directly with studies that have prevented EIAH but has been shown when CaO2 was increased to above-normal levels during exercise either with hyperoxia (25) or via increased Hb concentration (54). The major consequence of EIAH is probably its effect on convective O\(_2\) delivery to the working muscles. Theoretically, EIAH may also affect the unloading of O\(_2\) from muscle microcirculatory red blood cells and its subsequent diffusive movement into the myocytes. This is because the diffusion process is sustained throughout exercise. The results of the EIAH prevention studies in humans are consistent in showing that EIAH will reduce V\(_{\text{O}2}\)\(_{\text{max}}\) at least in trained subjects. The threshold of desaturation at which this effect is measurable is somewhat variable among subjects, but a consistent effect appears to be initiated at 3–4% O\(_2\) desaturation below resting levels. These threshold values are similar to those found when arterial hypoxemia was caused experimentally. The theories outlined above attribute the detrimental effects of EIAH on V\(_{\text{O}2}\)\(_{\text{max}}\) directly to an impairment of O\(_2\) delivery to the working locomotor muscles because of decreased CaO2; however, there are alternative explanations based on studies conducted in acute environmental hypoxia, suggesting that systemic hypoxemia may (indirectly) cause feedback inhibition of limb locomotor muscle force output in order to spare the function and/or oxygenation of more vital organ systems. Perhaps, then, it is the prevention of inadequate myocardial O\(_2\) supply (36), or excessive respiratory muscle work (24), or even central nervous system hypoxia (51) which limits the peak work rate of locomotor muscles in the presence of arterial hypoxemia. For example, the idea that EIAH means reduced O\(_2\) transport to the myocardium (as well as to the limbs) also leaves open the option that the relief of this hypoxemia may increase myocardial O\(_2\) supply, force of ventricular contraction, and Q (36). A companion concept requiring further testing is that changes in CaO2 affect limb blood flow inversely with the change in P\(_{\text{a}}\text{O}_2\), thereby resulting in no net change in O\(_2\) transport to the working limb (58). Any resulting change in V\(_{\text{O}2}\)\(_{\text{max}}\) is attributable, then, to differences in the V\(_{\text{O}2}\) of nonexercising tissues, such as hypoperfused splanchnic tissue. Finally, an important related question concerns the effect of EIAH on exercise performance per se, rather than on V\(_{\text{O}2}\)\(_{\text{max}}\). Two outcome measurements that are sometimes (but not always) closely related (35, 36). Hyperoxic O\(_2\) supplementation studies usually show a concomitant effect on exercise performance, but these effects may be substantially less than on V\(_{\text{O}2}\)\(_{\text{max}}\) (26, 35).

Summary: Unresolved Questions

Significant advances have been made, especially over the past decade, in describing EIAH and in understanding some of its causes and consequences to O\(_2\) transport and exercise performance; however, several fundamental problems remain unresolved, in many cases because we are unable to apply definitive measurements to the complex in vivo conditions present during maximum exercise. We have not yet accumulated sufficient defini-
tive descriptive data to know the true prevalence of EIAH and the effects of fitness level, gender, and/or healthy aging. How significant and widespread is the occurrence of excessive A–aDO₂ and EIAH during submaximal exercise and does this imply that EIAH results from a negative effect of training on lung structure, rather than merely a marked discrepancy between the adaptability of pulmonary vs. cardiovascular determinants of O₂ transport? Our techniques have as yet failed to provide a sufficiently clear window on lung function during heavy exercise so as to permit precise quantitation of extravascular lung water, or of morphological changes in the diffusion pathway or in the uniformity of red blood cell transit time distribution, or of inflammatory changes in the so-called “silent zone” of the lung’s peripheral airways. Accordingly, even the basic causes of VA/Q maldistribution and of diffusion limitation during exercise remain a mystery as do the reasons underlying the marked interindividual differences in propensity toward EIAH among athletes of similar levels of supranormal VO₂max. Similarly, without a valid measure of central neural respiratory motor output during exercise we are unable to explore whether, or under what specific conditions, feedback inhibition actually occurs or how true interindividual differences in ventilatory sensitivity may be assessed. Finally, and of appeal to scientists concerned with broader questions of exercise physiology, a century of research has left us still mystified by exactly how arterial hypoxemia limits VO₂max or exercise performance. Is the elusive concept of a “critical PO₂” in the muscle capillary or mitochondria for ATP generation valid or worthwhile?... and, specifically, what organ system involved directly or indirectly with O₂ transport is most vulnerable and, therefore, primarily responsible for the limitation of VO₂max in the presence of EIAH?

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