

Variations in exercise ventilation in hypoxia will affect oxygen uptake

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ABSTRACT

Reports of VO_2 response differences between normoxia and hypoxia during incremental exercise do not agree. In this study VO_2 and V_E were obtained from 15-s averages at identical work rates during continuous incremental cycle exercise in 8 subjects under ambient pressure (633 mmHg \approx 1,600 m) and during duplicate tests in acute hypobaric hypoxia (455 mmHg \approx 4,350 m), ranging from 49 to 100% of VO_2 peak in hypoxia and 42–87% of VO_2 peak in normoxia. The average VO_2 was 96 mL/min (619 mL) lower at 455 mmHg (n.s. $P = 0.15$) during ramp exercises. Individual response points were better described by polynomial than linear equations (mL/min/W). The V_E was greater in hypoxia, with marked individual variation in the differences which correlated significantly and directly with the VO_2 difference between 455 mmHg and 633 mmHg ($P = 0.002$), likely related to work of breathing (W_b). The greater V_E at 455 mmHg resulted from a greater breathing frequency. When a subject's hypoxic ventilatory response is high, the extra work of breathing reduces mechanical efficiency (E). Mean ΔE calculated from individual linear slopes was 27.7 and 30.3% at 633 and 455 mmHg, respectively (n.s.). Gross efficiency (GE) calculated from

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mean VO_2 and work rate and correcting for W_b from a V_E – VO_2 relationship reported previously, gave corresponding values of 20.6 and 21.8 ($P = 0.05$). Individual variation in V_E among individuals overshadows average trends, as also apparent from other reports comparing hypoxia and normoxia during progressive exercise and must be considered in such studies.

KEYWORDS

altitude acclimatization, hypobaric hypoxia, incremental exercise, mechanical efficiency, normobaric hypoxia, work of breathing

INTRODUCTION

Sophisticated techniques have been employed to quantify the direct relationship between exercise ventilation (V_E) and VO_2 , suggesting that the work of breathing (W_b) should be taken into account when VO_2 response is the dependent variable (1, 2). This has been rarely considered when comparing exercise VO_2 responses in normoxia and hypoxia in many situations and environments.

Studies comparing the amount of oxygen consumed in response to incremental or stepwise exercise between normoxia and hypobaric have received considerable attention by exercise physiologists. Inequality in the VO_2 responses over the same work rate range has been attributed to differences in anaerobic metabolism (3–5), time lags in the rise time of VO_2 (6, 7), mechanical efficiency (8), and O_2 stores (9). The VO_2 response characteristics have also been used to assess changes with acclimatization to hypoxia and exercise training, with dissimilar results (10, 11). Investigators often assume a linear relationship between VO_2 and work rate (slope: mL/min/W) in these studies, often to calculate and compare delta efficiency (ΔE). However, the average VO_2 or total O_2 consumed during incremental exercise can be obtained without the assumption of linearity to estimate gross efficiency (GE). A few reports have indicated that VO_2 is lower during incremental exercise in hypoxia over the same power output (5, 12, 13), suggesting increased mechanical efficiency, but some disagree (14). Inspections of averaged data from many studies where VO_2 –work rate relationships during exercise in hypobaric hypoxia and normoxia are available favor a lower VO_2 and lower slope in hypoxia than normoxia (15–19).

Some studies have reported that the mechanical efficiency of exercise is reduced in acute hypobaric hypoxia (8, 20) or increased when breathing hypoxic gas mixtures (5) relative to lower equivalent altitudes. Findings are not consistent and discrepancies may be due to variations in exercise testing protocols, gas exchange measuring devices, differences in ventilatory responses and definitions of mechanical efficiency.

This study compares the total oxygen consumed in hypobaric hypoxia (455 mmHg) and normoxia (ambient: 633 mmHg) during incremental exercise in the same subjects over identical work rates from ≈ 46 to 94% of VO_2 peak without assuming slope linearity. The focus is on the effect that variability among subjects in the hypoxic ventilatory response might have on the difference of the VO_2 response between normoxia and hypoxia.

Substantial variation in individuals' hypoxic ventilatory drive during exercise will affect the quantification of differences in pulmonary gas exchange between normoxia and hypoxia. This



must be taken into consideration in studies of mechanical efficiency, evaluation of altitude acclimatization, and any exercise studies that involve hypoxia.

METHODS

These data were obtained during a research study previously reported with a different focus (21–23). Eight male volunteers were cyclists and runners consistently performing an average of 6 hr/wk of moderate and 2–3 hr/wk of vigorous exercise during the year prior to, and during the study. Means \pm SD for VO_2 peak, age and weight were 55 ± 5 mL/min/kg, 28 ± 6 yr and 75.4 ± 8.4 kg, respectively. All subjects resided between 1,500 and 1,600 m for at least 6 months before the study and during data collection. Written informed consent was obtained, as approved by the Human Research Review Committee at the University of New Mexico.

Each subject completed two incremental VO_2 peak tests. One test took place under ambient conditions at 633 ± 3 mmHg (1,600 m) and one following acute exposure to reduced pressure in a decompression chamber at 455 ± 1 mmHg, equivalent to 4,350 m according to the equation of West (24). All subjects first completed the test at 633 mmHg with hypobaric chamber doors open, and 6–9 days later performed the test at 455 mmHg. Subjects were tested at the same time of day at both pressures and refrained from strenuous exercise, caffeine, and alcohol for 24 hr prior to testing. The average ambient temperature for all tests was 22 ± 2 °C. For tests at 455 mmHg the “ascent” rate was 20 mmHg/min; subjects then rested approximately 30 min prior to initiating exercise.

The VO_2 peak tests were performed on an electronically-braked cycle ergometer (Velotron DynaFit Pro, RacerMate, Spearfish, SD). Gas exchange was continuously measured breath-by-breath with a metabolic cart (ParvoMedics True One 2400, Sandy, UT). Heart rate (HR) was continuously monitored via telemetry (Polar Electro, model FS1, Woodbury, NY), while O_2 saturation (SpO_2) was measured by finger pulse oximeter (GO_2 Pulse Oximeter, Philips Respironics, Andover, MA). Cycling at each subject’s preferred cadence began at 70 W for the first minute and the work rate then increased 35 W every minute until volitional fatigue or inability to maintain the work rate. The average exercise time to reach VO_2 peak was 9.5 ± 1.4 min at 633 mmHg and 8.5 ± 1.5 min at 455 mmHg. The average of VO_2 and associated ventilatory measurements over 15-s intervals from 33 to 100% of peak work rate were recorded. Each 35-W work rate increment was divided into four quarters to coincide with the 15-s measurement intervals. The average number of recorded points for the 16 tests was 22 (range: 16–26). The measured values for the tests at 633 and 455 mmHg were then superimposed and compared at identical work rates. The analyzed points at 455 mmHg included those between 49 and 100% of VO_2 peak and at 633 mmHg those between 42 and 87% of VO_2 peak because of the 15% average reduction of VO_2 peak by all subjects at 455 mmHg.

Calculations and statistics

The average VO_2 , V_E , and other gas exchange measurements within the work rate range for each subject was obtained by summing all values within the range and dividing by the number of points. These averages for each of the 8 subjects were compared at 633 and 455 mmHg by paired *t*-test. As an example, the VO_2 values for one subject are shown in Fig. 1A and the



corresponding V_E values in Fig. 1B. The VO_2 curves shown in Fig. 1A are those obtained by a 2nd order polynomial equation ($\text{VO}_2 = A + BW + CW^2$) because retrospectively the integrated value of this equation divided by the work rate range closely approximated the averaged values, as the mean \pm SD of the absolute differences for VO_2 for the 16 curves was 2.6 ± 1.6 mL/min. The O_2 difference in mL between 455 and 633 mmHg is represented by the area denoted “X” in Fig. 1A. This value of $-2,504$ mL was obtained by multiplying the VO_2 difference (mL/min) between 455 and 633 mmHg by exercise time, i.e., $[(2,606 - 3,042) 201\text{W}/35\text{W}/\text{min}]$. In Fig. 1A the positive coefficient of the C term at 455 mmHg indicates upward curvature and the small negative term in normoxia indicates downward curvature. The curves for V_E were obtained by integration of the equation $\ln(V_E) = A + B(W)$, as the mean \pm SD of these absolute differences from the averaged values was 0.6 ± 0.3 L/min.

The VO_2 vs. work rate slope is utilized to obtain ΔE (25, 26), which is defined as, “the quotient of an amount of extra external mechanical power to the increase in metabolic power needed to overcome this amount of extra external mechanical power” (27). The VO_2 values are converted to metabolic power with the constant of 0.00505 Kcal/mL of O_2 at RER = 1.00 determined by Lusk (28). By multiplying VO_2 (mL/min) by 4186 J/Kcal and min 60/s, the metabolic power in units of J/s is obtained and ΔE in percent is: $100 \times [1/(\text{mL}/\text{min}/\text{W} \times 0.3523)]$. Thus, a decrease in slope indicates an increase in ΔE . The ΔE is theoretically preferred to GE and net efficiency because of the difficulties in making baseline subtractions for VO_2 at rest for the latter (29).

Data are reported as means \pm SD. Paired t -tests were used to determine significance of differences between gas exchange measurements at 633 and 455 mmHg. The significance of the linear slope differences between pressures was computed by t -test, as described by Crow et al. (30). The significance of differences between linear and polynomial fits to the data was determined by F -tests. The correlation coefficient between variables was obtained by least squares linear regression. The level of significance was $P \leq 0.05$.

RESULTS

Comparison of VO_2 over equal work rate ranges at 455 and 633 mmHg

The average of mixed expired PCO_2 , PO_2 , and SpO_2 during the work rate range was significantly lower at 455 mmHg compared to 633 mmHg (24.4 ± 3.1 vs. 31.0 ± 3.8 mmHg and 60.9 ± 3.6 vs. 90.4 ± 3.8 mmHg) and 76.7 ± 2.8 vs. $93.1 \pm 2.4\%$, respectively. The average respiratory exchange ratio (RER) and HR tended to be higher at 455 mmHg (1.01 ± 0.05 vs. 0.95 ± 0.05 and 151 ± 12 vs. 141 ± 15 b/min), $P = 0.07$ for both.

The individual values for the 8 subjects for O_2 and ventilatory components are shown in Table 1 as determined over the course of exercise as the average of the individual 15-s averages. The corresponding linear slope values are also indicated. At 455 mmHg the average O_2 uptake was 619 mL lower than at 633 mmHg for 6 of the 8 subjects, but was not significant. These O_2 differences were not significantly correlated with the differences in linear slopes ($P = 0.30$). However, VO_2 at both pressures correlated significantly with V_E , and the work rate range, which is to be expected as the latter varied among subjects. The V_E was better correlated with the work rate interval at 633 mmHg ($r = 0.66$, $P = 0.07$) than at 455 mmHg ($r = 0.29$, $P = 0.49$). The positive correlation between the differences between pressures in ΔVO_2 and ΔV_E was significant



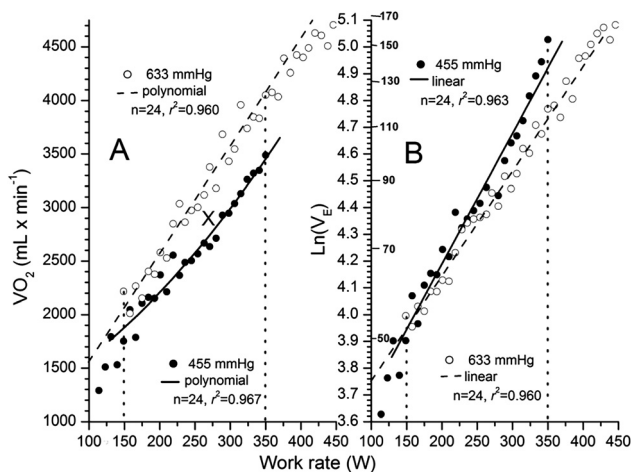


Fig. 1. VO_2 and V_E measurements for subject 1. Panel A: VO_2 values are averaged over the same work rates from 149 to 350 W at 455 and 633 mmHg. At 633 mmHg: $\text{VO}_2 = 3,042$ and at 455 mmHg: $\text{VO}_2 = 2,606$, for a difference of -436 mL/min or $-2,504$ mL ($-436 \times 201/35$) denoted as area X as indicated in Table 1. The difference between the integration of the best fit polynomial equations at 633 mmHg [$Y = 486 + 10.55(X) - 0.0012(X^2)$] and 455 mmHg [$Y = 1,174 + 3.36(X) + 0.0090(X^2)$] between the dotted lines gives corresponding values of 3,043, 2,603, and -440 mL/min. Panel B: At 633 mmHg: $V_E = 78.9$ L/min and at 455: $V_E = 88.0$ L/min, for a difference of 9.1 L/min. Integration of the best fit linear equations of $\text{Ln}(V_E)$ vs. W at 633 mmHg [$Y = 3.3619 + 0.0039(X)$] and 455 mmHg [$Y = 3.2126 + 0.0049(X)$] gives corresponding values of 78.7, 87.4, and 8.7 L/min

($P = 0.028$). This is summarized in Fig. 2A where percent changes for VO_2 and V_E are shown to take into account body size differences. Fig. 2B shows that the breathing frequency difference (Δf_R) also correlates highly with the ΔVO_2 difference and is the main contributor to the variability of ΔV_E , indicated by a coefficient of variation of 60%. This is also indicated by the r -value between ΔV_E vs. Δf_R of 0.96 ($P < 0.001$). The difference in tidal volume (ΔV_T) also correlates significantly with ΔVO_2 , but these changes are relatively small, as the increase in V_E with hypoxia is $\approx 97\%$ due to f_R increases. The relationship between ΔV_T and Δf_R was negative ($r = -0.52$), but not significant, suggesting that increases in Δf_R in hypoxia overrode possible increases in V_T . The correlations of V_E , f_R , and V_T differences with linear slope differences in Table 1 were not significant, with r -values of 0.08, 0.26, and 0.44, respectively.

The values for ΔE , calculated from the slopes in Table 1 were $27.7 \pm 1.7\%$ at 633 mmHg and $30.3 \pm 3.8\%$ at 455 mmHg, but not significantly different ($P = 0.13$). The ΔE differences were not significantly correlated with ΔVO_2 ($r = -0.48$, $P = 0.23$). GE was calculated from VO_2 as $100 \times \Delta W \times 1/(\text{mL/min} \times 4186 \times 0.00505/60)$. These values are 19.5 ± 1.4 and $20.3 \pm 2.5\%$ at 633 and 455 mmHg, respectively, and were also not different between normoxia and hypoxia ($P = 0.23$), but these differences correlated highly with ΔVO_2 ($r = -0.98$), as expected. The GE values are lower than for ΔE because VO_2 now includes that at rest and work before 33% of the maximum work rate where recordings began.



Table 1. Mean \pm 1.0 SD values between $= 125 \pm 15$ and 312 ± 43 W for 8 subjects at 633 and 455 mmHg pressure

Subject (ΔW)	VO ₂ (mL/min)			Slope (mL/min/W)			V _E (L/min BTPS)			f _R (b/min)			V _T (L BTPS)		
	633	455	Δ (mL)	633	455	Δ	633	455	Δ	633	455	Δ	633	455	Δ
1 (201)	3,042	2,606	−2,504	9.97	7.85	−2.12	78.9	88.0	9.1	25.8	26.7	0.9	3.06	3.30	0.24
2 (202)	2,778	2,843	375	11.29	8.97	−2.32	81.8	115.9	34.1	27.2	37.8	10.6	3.01	3.07	0.06
3 (131)	2,128	2,424	1,108	10.21	10.90	0.70	57.8	108.7	50.9	24.0	45.7	21.7	2.41	2.38	−0.03
4 (201)	2,606	2,381	−1,292	9.44	9.40	−0.04	70.3	80.8	10.5	25.0	28.2	3.2	2.81	2.87	0.05
5 (219)	3,000	2,848	−951	10.41	8.32	−2.09	84.5	110.8	26.3	27.4	34.3	6.9	3.08	3.23	0.15
6 (184)	2,787	2,640	−773	10.32	9.05	−1.27	97.9	118.6	20.7	33.7	40.4	6.7	2.91	2.94	0.03
7 (210)	3,092	2,976	−696	11.01	10.63	−0.38	73.9	110.9	37.0	26.6	37.1	10.5	2.78	2.99	0.21
8 (149)	2,265	2,213	−221	9.60	10.87	1.26	52.8	63.6	10.8	21.0	24.6	3.6	2.51	2.59	0.07
Mean	2,712	2,616	−619	10.28	9.50	−0.78	74.7	99.7	24.9	26.3	34.4	8.0	2.82	2.92	0.10
SD	358	265	1,087	0.64	1.18	1.37	14.6	19.8	15.0	3.6	7.3	6.5	0.25	0.31	0.09
P diff.			0.15			0.15			0.002			0.010			0.020
r vs. Δ VO ₂			−			0.42			0.76			0.84			−0.74
Sign. of r			−			0.30			0.028			0.009			0.037

ΔW : work rate range for each subject.

Δ (mL) is calculated as (VO₂ at 455−VO₂ at 633) \times W/35W/min.

Bold: $P < 0.05$.

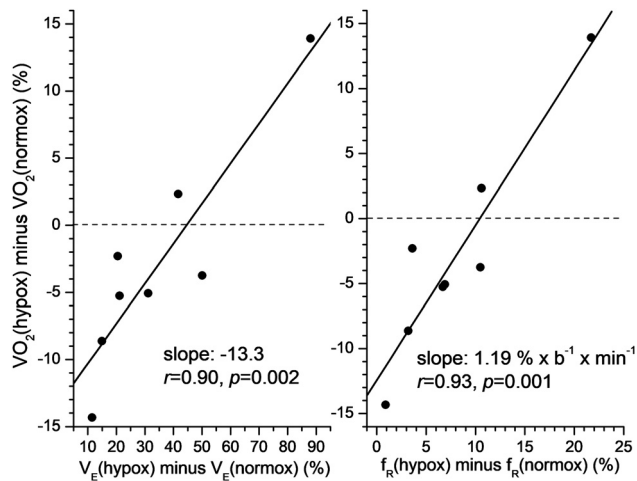


Fig. 2. Panel A: Significant relationship between percent change in VO_2 and V_E from 633 mmHg to 455 mmHg in 8 subjects. Panel B: Significant relationship between increase in f_R and percent change in VO_2 from 633 mmHg to 455 mmHg in 8 subjects

Comparison of combined VO_2 vs. work rate measurements

The 179 points for all subjects at both pressures, each a 15-s average of VO_2 , are shown in Fig. 3, with the curves of the polynomial equations that describe the two sets of data points, with linear

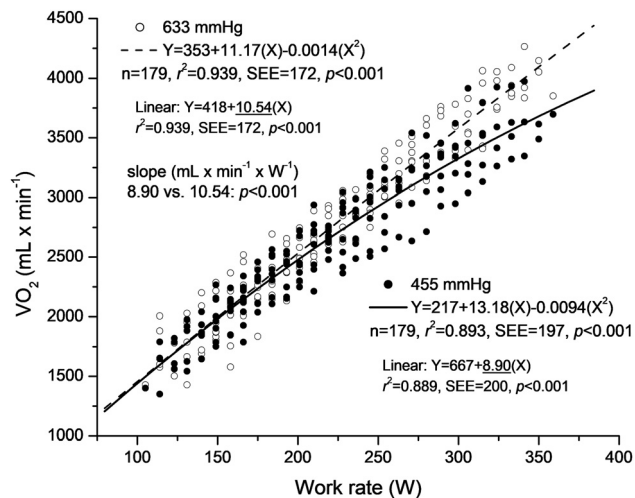


Fig. 3. Individual data points (179) for 8 subjects from ≈ 46 to 94% of VO_2 peak at 455 and 633 mmHg. The lines calculated by best fit polynomial and linear equations are indicated



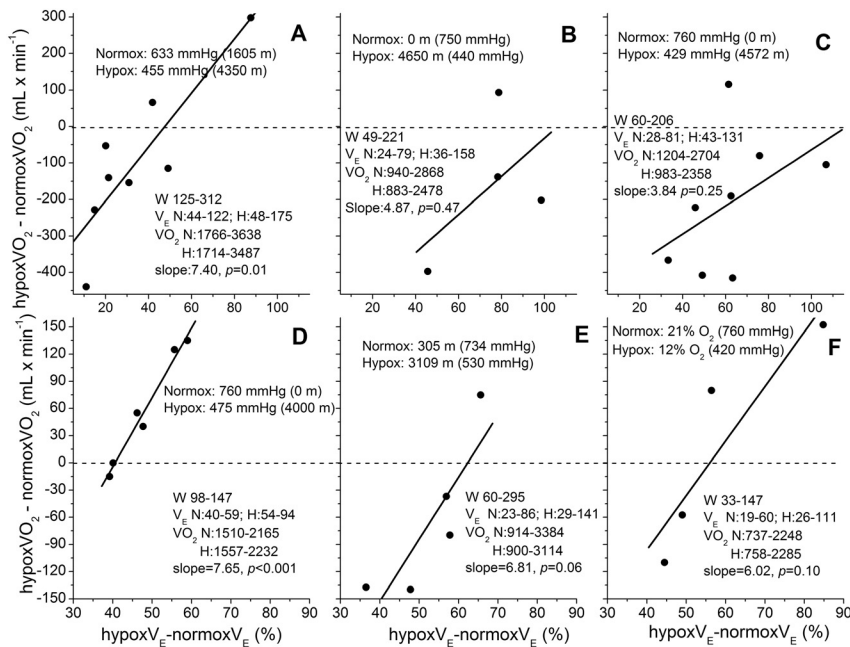


Fig. 4. Association of percent increases of V_E in hypoxia over normoxia and corresponding VO_2 difference during incremental exercise from individuals in 6 studies. Data for V_E and VO_2 for each study were analyzed as shown in Fig. 1A and B. Panel A: this study, with continuous ramp cycling in hypobaric hypoxia. Panel B: from Pugh et al. (16), with continuous and discontinuous ramp cycling at altitude. Panel C: from Sutton et al. (18) and Reeves et al. (36) in OEII, with continuous and discontinuous ramp cycling in hypobaric hypoxia. Panel D: from Stenberg et al. (37), with discontinuous cycling in hypobaric hypoxia. Panel E: from Reeves et al. (17), with discontinuous treadmill running at altitude. Panel F: from Hughes et al. (38), with continuous cycling with hypoxic gas mixture. All relationships are positive, indicating an average increase of 6 mL/min of VO_2 above normoxia per one percent increase in V_E . The average increase in peak V_E with hypoxia is 70%; indicating that W_b could have contributed ≈ 420 mL/min to peak VO_2 in hypoxia. The average minimum and maximum values for subjects in each study are noted for work rate (W), V_E and VO_2 in normoxia (N) and hypoxia (H), with linear slopes of regressions shown

equations also indicated in the legend. The best fit linear least squares regression slope at 455 mmHg ($P_{iO_2} = 85$ mmHg) is 8.90 and is significantly lower ($P < 0.001$, $t = 5.27$) than the 10.54 value at 633 mmHg ($P_{iO_2} = 123$ mmHg). The polynomial fits to the data points suggest downward curvature at both pressures, barely noticeable at 633 mmHg, but more apparent at 455 mmHg. However, an F -test comparing the variances of the linear vs. polynomial fit at 633 mmHg resulted in $P = 0.51$ ($F = 0.995$) and $P = 0.42$ ($F = 1.032$) at 455 mmHg. Thus, there is no evidence that the polynomial fit is statistically superior at either pressure for the grouped points.



DISCUSSION

A large variation in individual's V_E response to hypoxia has been previously reported and characterized (31). Undoubtedly the increased work of breathing (W_b) contributes to the close correlation between differences in V_E and $\dot{V}O_2$ noted in Fig. 2A. The O_2 cost of breathing can amount to 10% or more of total $\dot{V}O_2$ during maximal exercise hyperpnea as the cost rises exponentially with work rate (1, 2). For example, subject 2 in Table 1 reached a maximal V_E of 184 L/min at 455 mmHg, compared to 85 L/min at the same work rate at 633 mmHg. This difference in V_E amounts to ≈ 322 mL/min of $\dot{V}O_2$ according to the W_b vs. V_E relationship reported by Dominelli et al. (2), where $\dot{V}O_2 = 1.04 + 52.6 e^{(V_E/84.3)}$. Any reduction in W_b from reduced air density at 455 mmHg is likely of minor influence because at 455 mmHg the V_E is higher and bronchoconstriction (32) and interstitial pulmonary edema (19) due to hypoxia probably contribute to W_b . The increased cost at 455 mmHg is likely further enhanced by the higher f_R which may be above the optimal frequency to minimize W_b (33, 34). The W_b vs. V_E relationship above would reduce the mean $\dot{V}O_2$ averages in Table 1 by 138 and 190 L/min at 633 and 455 mmHg, respectively.

The $\dot{V}O_2$ values shown in Fig. 3 are the same below ≈ 175 W. This is not surprising, as the slope has been reported to be similar in normoxia and hypoxia during steady state submaximal exercises at lower work rates at simulated altitude (22) and with hypoxic gas mixtures (12). Linear slopes of the curves in Fig. 3 are generally similar to the average curves during incremental exercise utilizing hypoxic gas mixtures previously reported (13, 35). However, the significant difference in linear slopes between 633 and 455 mmHg in Fig. 3 is misleading as a general axiom because only 4 of the individual comparisons showed a significantly lower slope at 455 mmHg, with a higher slope at 633 mmHg occurring in 2 of 8 subjects (n.s.), with essentially no difference in 2 subjects. A polynomial fit to the individual $\dot{V}O_2$ vs. work rate curves resulted in three positive values for the C term at 633 and two at 455 mmHg (upward curvature, presumably related to enhanced W_b) and 5 negatives values at 633 and 6 at 455 mmHg (downward curvature, presumably related to anaerobic metabolism). To avoid the questionable assumption of linearity it seems more appropriate to utilize the individual differences in $\dot{V}O_2$ or O_2 (mL) in Table 1, rather than average curve slope shown in Fig. 3 to quantify differences between the normoxia and hypoxia.

The direct relationship between V_E and $\dot{V}O_2$ shown in Fig. 2 is further supported by inspection of other reported studies indicated in Fig. 4, where individual subject's data were available for exercise in hypoxia and normoxia at the same work rates. These plots were constructed from five studies where four or more points were reported for individual subjects as referenced in the figure legend, using polynomial fits to $\dot{V}O_2$ and linear fits to $\ln(V_E)$ vs. work rate as described in Fig. 1A and B. The change in $\dot{V}O_2$ from normoxia to hypoxia is clearly related to the percentage increase in V_E (BTPS) by individuals in these diverse studies and subjects, even though statistical significance of the relationships is inconsistent, mainly due to the paucity of subjects.

$\dot{V}O_2$ differences in normoxia and hypoxia during incremental exercise

Table 1 and Fig. 4 indicate that $\Delta\dot{V}O_2$ vs. Δ work rate slope differences between normoxia and hypoxia are mainly attributable to individual variations in the V_E response to hypoxic exercise.



The VO_2 differences measured over a range of continuous or discontinuous incremental work rates, rather than the calculated linear slope of VO_2 seem more accurate for estimating differences between hypoxia and normoxia because minor deviations from linearity will have an appreciable effect on the result. For example, if differences in efficiency at 633 and 455 mmHg are of interest, to avoid the assumption of linearity GE can be calculated from VO_2 values in Table 1 for the 8 subjects and reducing VO_2 for V_E predicted according to the relationship by Dominelli et al. (2) above. These “non-respiratory” values are 20.6 ± 1.6 and 21.8 ± 2.6 and are now significantly different between 633 and 455 mmHg ($P = 0.05$). The corresponding mean GE values for the five studies shown in Fig. 4 are 21.1 ± 7.8 and $22.7 \pm 8.9\%$ in normoxia and hypoxia, respectively.

Some studies report that an increase in anaerobic metabolism contributes to the lower VO_2 rise during exercise in hypoxia because as exercise in hypoxia progresses there is an increasing contribution by this energy source (3–5, 13). Unless compensated for by increased W_b , this would tend to lower the VO_2 vs. work rate slope at higher work levels and result in a lower overall slope and higher ΔE , especially at 455 mmHg, which was not the case here. The present study suggests that a greater increase in V_E will offset a decrease in VO_2 in hypoxia during exercise because there was no greater downward curvature in 8 individuals in hypoxia, as indicated by the C term in the polynomials being only slightly more negative at 455 mmHg than at 633 mmHg ($t = 0.22$, $P = 0.89$).

A time lag in VO_2 during a ramp exercise while breathing hypoxic gas has also been proposed (4, 6, 7). These studies suggest that when the exercise stages during a continuous incremental exercise are too large the VO_2 will lag behind in response to each load increment, thus reducing the slope. In partial contradiction to this, and the proposed greater anaerobic metabolism in hypoxia, is the observation that the post-exercise O_2 consumption after peak intensity exercise is similar in hypoxia and normoxia (39–43).

Another consideration is that the O_2 kinetics after the onset of exercise is affected by a reduction in body O_2 stores (9). This is important when beginning exercise in hypoxia, as in the present study, where the initial phase of exercise will exhibit a lower VO_2 at the mouth while body O_2 stores are utilized. This early reduction in VO_2 as blood O_2 saturation decreases would increase the overall VO_2 vs. work rate slope.

The lower density of the inspired air in hypobaric hypoxia in this study required $V_E(\text{BTPS})$ to increase over the average work interval by 44% to supply the same VO_2 , but the average $V_E(\text{STPD})$ increased only 33%. This deficiency in $V_E(\text{STPD})$ during acute hypoxia (presumably because of the acute nature of the hypoxia) may predispose the VO_2 to be lower in hypoxia. The actual V_E response to maintain the O_2 requirements of the increasing workloads will vary with the sensitivity of the hypoxic chemoreceptors of the individual subjects. Ventilation during exercise increases at given work rates with altitude acclimatization (44, 45) and by affecting VO_2 may also contribute to the inconsistent conclusions regarding the effect of acclimatization on efficiency estimates computed from the VO_2 –work rate slopes that was mentioned earlier.

In summary, these findings suggest that the variations in V_E responses to exercise in hypobaric hypoxia may contribute substantially to the inconsistent results of previously reported comparisons of VO_2 and computations of efficiency between normoxia and hypoxia during incremental exercise. These data suggest a slightly smaller VO_2 for the same work rate at 455 vs. 633 mmHg, but certainly studies with more subjects are required for confirmation. The variation of V_E responses to hypoxia of selected research subjects must be taken into account in studies



comparing gas exchange at different levels of PIO_2 and linear presumptions of VO_2 vs. work rate relationships can be misleading.

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