ORIGINAL ARTICLE

The effect of breathing an ambient low-density, hyperoxic gas on the perceived effort of breathing and maximal performance of exercise in well-trained athletes

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Background: The role of the perception of breathing effort in the regulation of performance of maximal exercise remains unclear.
Aims: To determine whether the perceived effort of ventilation is altered through substituting a less dense gas for normal ambient air and whether this substitution affects performance of maximal incremental exercise in trained athletes.
Methods: Eight highly trained cyclists (mean SD) maximal oxygen consumption (VO_2max) = 69.9 (7.9) (mlO_2/kg/min) performed two randomised maximal tests in a hyperbaric chamber breathing ambient air composed of either 35% O_2/65% N_2 (nitrox) or 35% O_2/65% He (heliox). A ramp protocol was used in which power output was incremented at 0.5 W/s. The trials were separated by at least 48 h. The perceived effort of breathing was obtained via Borg Category Ratio Scales at 3-min intervals and at fatigue. Oxygen consumption (VO_2) and minute ventilation (V_E) were monitored continuously.
Results: Breathing heliox did not change the sensation of dyspnoea: there were no differences between trials for the Borg scales at any time point. Exercise performance was not different between the nitrox and heliox trials (peak power output = 451 (58) and 453 (56) W), nor was VO_2max (4.96 (0.61) and 4.88 (0.65) l/min) or maximal V_E (157 (24) and 163 (22) l/min). Between-trial variability in peak power output was less than either VO_2max or maximal V_E.
Conclusion: Breathing a less dense gas does not improve maximal performance of exercise or reduce the perception of breathing effort in highly trained athletes, although an attenuated submaximal tidal volume and V_E with a concomitant reduction in VO_2 suggests an improved gas exchange and reduced O_2 cost of ventilation when breathing heliox.

Sensations of respiratory discomfort are consciously monitored during exercise,[1] and, at higher workloads, sensations of dyspnoea are closely related to perceived exertion.[2 3] This evidence indicates a potential role for afferent sensory feedback of ventilatory exertion from the respiratory muscles in regulating maximum performance of exercise in humans.[4] However, the role of perceived respiratory effort in the regulation of maximal performance of exercise remains unclear.[5]

Perception of respiratory effort can be manipulated by altering the work of breathing. This effect has traditionally been achieved by either using a pressure-assisted ventilation (PAV) device, in which a demand valve senses pressure changes at the nose and mouth and reactively assists the breathing,[6 7] or altering the properties of the inspired air so that it is less dense than normal air and therefore reduces the work required to move the air in and out of the lungs.[8–10]

A serious limitation to the PAV method is the potential to disrupt the normal breathing pattern of the subjects, as the novelty of the task requires subjects to "train" to breathe on the apparatus before undergoing testing.[7] A further limitation is the delayed response time of the demand valve to pressure changes at the mouth.[7] The result is that the PAV method can only be used effectively during steady-state exercise and therefore cannot assess the role of ventilatory work or its associated sensations as a factor limiting progressive maximal exercise to exhaustion. Studies have produced mixed results regarding the effects of unloading the work of the respiratory muscles on exercise capacity possibly as a result of these limitations.[6 7]

By contrast, the performance benefits of breathing a less dense gas have produced more consistent results.[8 10–12] However, the increased breathing resistance imposed by the external gas delivery and collection systems used in these studies creates a potential difficulty in differentiating between the effects of the lighter gas on the anatomical respiratory tree and on the external respiratory tubing.[13 14] Furthermore, altering the properties of the inspired air may result in altered ventilatory dynamics. Although some researchers[15 16] have suggested that a less dense carrier gas might increase the alveolar–arterial partial pressure of oxygen (pO_2) gradient, thereby reducing arterial blood oxygen saturation, Nemery *et al*[17] reported that the physical properties of the inspired gas do not affect ventilatory dynamics. Indeed, more recent studies have found that breathing a helium–oxygen mix improved arterial saturation.[9 18] Therefore, it seems that breathing a less dense gas during high-intensity exercise may improve alveolar ventilation or the alveolar–arterial O_2 difference or both, thereby enhancing the oxygen content of arterial blood.[5 19]

To fully elucidate any potential role for the perceived effort of breathing in regulating maximal exercise, the confounding effects of breathing a gas less dense than air need to be considered. Conducting a trial on the performance of exercise in an environment in which "lighter" air is substituted for the ambient air will negate the need for external breathing

Abbreviations: ANOVA, analysis of variance; COPD, chronic obstructive pulmonary disease; CR_{10}, Category-Ratio Scale; F_iO_2, fractional inspired oxygen; PAV, pressure-assisted ventilation; RPE_{15}, 15-point rating of perceived exertion apparatus, and hence the confounding effects of unloading the added respiratory resistance caused by such an apparatus. Furthermore, any ergogenic benefits derived from improved pulmonary dynamics can be minimised by increasing the fraction of oxygen in the inspired air.[19]

Young *et al*[20] showed that physically active subjects are able to differentially assess feelings of effort pertaining to the respiratory and cardiovascular systems. Therefore, we aimed to investigate the perceptual and performance effects of breathing a low-density, hyperoxic gas during a graded maximal exercise test to exhaustion in a young, physically fit population. We hypothesised that breathing a less dense gas would attenuate the perceived effort of breathing and improve incremental exercise time to exhaustion.

METHODS

Subjects

Eight highly trained cyclists (mean standard deviation (SD)) maximal oxygen consumption (VO_2max) = 69.9 (7.9) ml O_2/kg/min) were recruited for this study, which was approved by the university research and ethics committee. This study complied with the Declaration of Helsinki as adopted at the 52nd World Medical Association General Assembly, Edinburgh, October 2000. The nature of the study, including the risks associated with exercising in oxygen and helium-enriched conditions, was clearly explained to the subjects, from whom informed consent was obtained before the initiation of testing. The mean (SD) age, height and weight of the subjects were 20.1 (1.2) years, 184.4 (5.6) cm and 69.6 (5.1) kg, respectively. Subjects were excluded from the study if they smoked, had breathing disorders, or had experienced a respiratory illness within 2 weeks of the start of the study.

Experimental protocol

After a habituation trial in normoxic conditions, each subject was required to perform an incremental ramp cycle test to exhaustion on a Lode cycle ergometer (Excalibur, The Netherlands) on two separate occasions, while breathing a hyperoxic (nitrox) mixture (fractional inspired oxygen (F_iO_2) of 35% and the balance nitrogen) and a helium (heliox) mixture (F_iO_2 of 35% and the balance helium). The tests lasted on average 605 s (range 437–757). The hyperoxic concentration of 35% was selected on the basis of previously published literature on heliox breathing[21,22] and the reversal of exercise-induced arterial hypoxaemia.[19]

Consecutive tests were separated by at least 2 days, but were not more than 7 days apart. The testing order was randomised and single-blinded, as the experimenter but not the cyclist was always aware of the nature of the gas composition in the chamber. The cycle ergometer ramp protocol consisted of a 2-min warm-up ride at 150 W; thereafter, the workload of the ramp protocol increased by 0.5 W/s to volitional exhaustion.[23] The subjects cycled inside a Multi-place Class ''A'' 18 000 l hyperbaric chamber of length 3.5 m and diameter 2.5 m, built to Lloyd's and American Society of Mechanical Engineers 1 Pressure Vessels for Human Occupancy specifications. There were internal CO_2 scrubbers; O_2, temperature and humidity were continuously monitored. Oxygen content was maintained at the prescribed level for all the trials. Owing to the thermal properties of helium, the average temperature and humidity levels tended to be slightly lower in the heliox trials (21℃ and 49% *v* 24℃ and 63%). The air pressure inside the chamber was maintained at sea level for all the trials.

The chamber was completely flushed through twice with the relevant ambient gas mixture after the subject and investigator had entered the chamber and the chamber door had been sealed. Talking inside the chamber was not permitted, as helium in the air alters the timbre of the human voice and would have been immediately obvious to the experimental subjects. The chamber was not pressurised for either test, and a fan maintained continual air movement in the chamber to prevent any gas layering that might occur with a low-density gas mixture. The concentration in the chamber was continuously monitored at the height of the cyclist's head, and any drift away from the required O_2 concentration was corrected by the chamber director who ensured an inflow of the relevant gas mixture into the chamber until the requisite F_iO_2 was regained. This ensured that the F_iO_2 did not differ from the prescribed concentration by >1–2%.

Before each test, subjects sat quietly for 10 min in the chamber while breathing the imposed gas mixture to ensure adequate equilibration of the inhaled gas mixtures throughout the body, and to also ensure complete mixing of the new gas mixture throughout the chamber. The test was followed by a recovery period during which the chamber was flushed through twice with room air to preclude the subjects identifying the nature of the gas mixture that had been present during their trials. Silence was maintained during the recovery period.

Expired respiratory gas analyses

For the measurement of oxygen consumption (VO_2) and minute ventilation (V_E) during the tests, subjects wore a mask covering the nose and mouth. The expired air passed through an online breath-by-breath gas analyser and pneumotach (Cardiovit CS-200 Ergo-Spiro; Schiller, Switzerland) and was averaged over 10-s intervals. Before each test, the gas analyser was calibrated by a span gas of known composition, and the pneumotach was calibrated with a 2-litre syringe. Both the gas analyser and the pneumotach were calibrated in situ. Peak VO_2 (VO_2peak) and V_E ($V_E$peak) were defined as the highest 10-s averages measured during the test.

Rating of perceived exertion

Levels of exertion were quantified on two different scales, the Borg 15-point rating of perceived exertion (RPE) scale (RPE_{15}) and the Borg Category-Ratio Scale (CR_{10}). Printed instructions were provided to familiarise subjects with each scale before their first incremental ramp test. Subjects were asked to provide an appropriate single score on the 15-point scale that was the best representation of their overall level of exertion. No help was given by the researcher in translating their feeling into numerical ratings on the RPE scale. The Borg CR_{10} exertion scale was used to quantify exertion localised specifically to the effort of breathing. The category-ratio scale was selected to measure localised exertion, because the growth of this scale more closely parallels the exponential increase in the ventilation during progressive exercise to exhaustion.[24] Readings were taken at 2 min and then at 3-min intervals thereafter.

Statistical analyses

For maximum data variables, a paired-samples Student's t test was performed to identify significant differences. The first 6 min of submaximum data were analysed. Repeated measures analysis of variance (ANOVA) was used to assess differences between and within the trials for submaximum data. When an ANOVA identified significant condition×time interaction, a retrospective Student's t test was performed. A Bland–Altman plot was used to identify bias in maximal values between the trials. Significance was accepted at $p<0.05$. All data are expressed as mean (standard error).

RESULTS

Maximum values of power output, VO_2 and V_E

Peak power achieved was not significantly different between trials (nitrox = 451 (58) W; heliox = 453 (56) W; p = 0.4). The

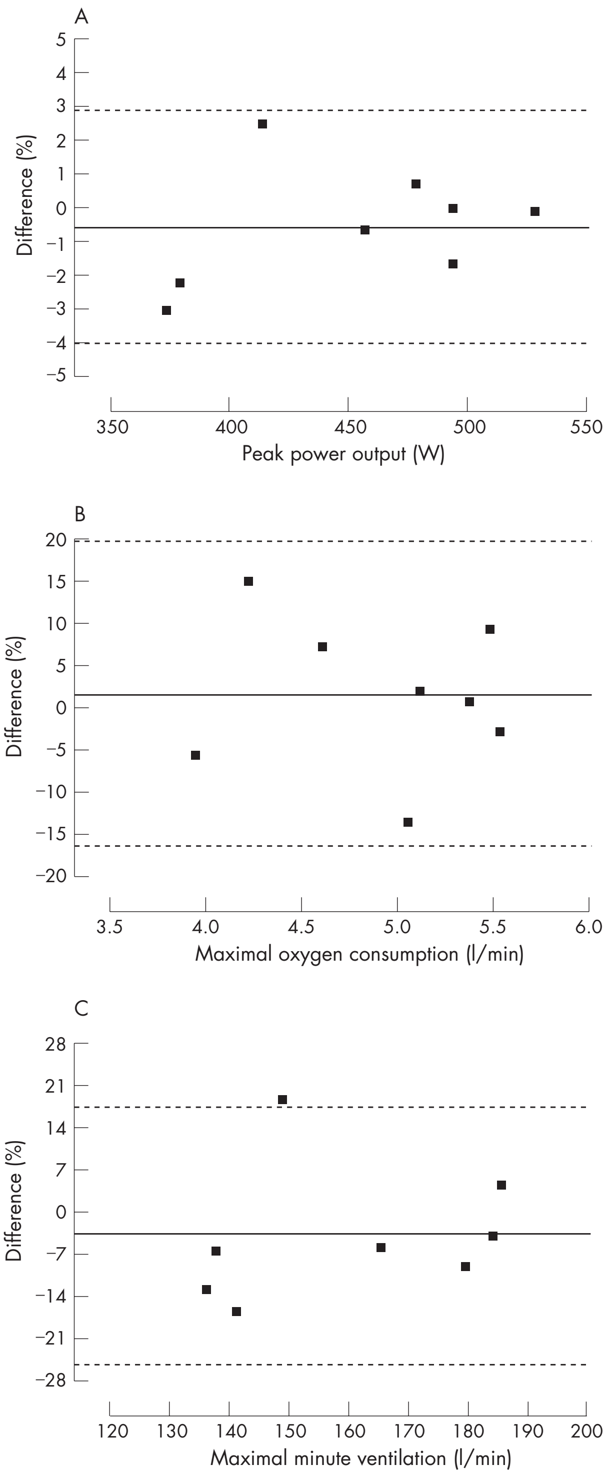

Figure 1 Bland–Altman plots depicting the percentage bias and individual percentage differences (mean (1.96 standard deviations)) for peak power output (A), maximal oxygen consumption (B) and maximal minute ventilation (C).

VO_2max was also similar for both conditions (nitrox = 4.96 (0.61) l/min; heliox = 4.88 (0.65) l/min; p = 0.6), as was maximal minute ventilation (nitrox = 157 (24) l/min; heliox = 163 (22) l/min; p = 0.3). The percentage bias between the means of the nitrox and heliox trials for peak power, VO_2 and V_E are −0.55 (1.77), 1.67 (9.19) and −4.02 (11), respectively (fig 1).

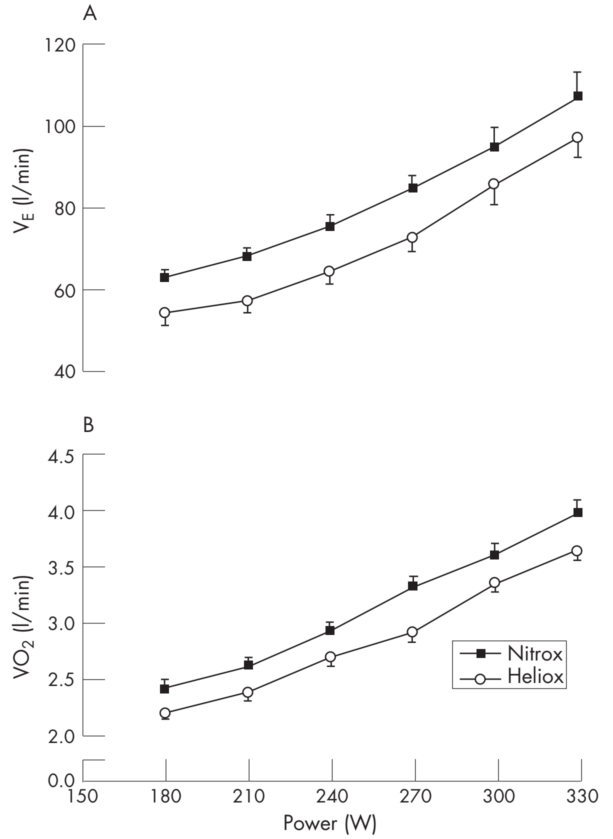

Figure 2 Mean (standard error) data for submaximal oxygen consumption (A) and submaximal minute ventilation (B) during incremental exercise performed in a sealed chamber under conditions of 30% O_2:70% N_2 (nitrox) and 30% O_2:70% He (heliox). *Significant trial effect (p<0.05).

Submaximum values of VO_2 and V_E

Figure 2 depicts changes in oxygen consumption and minute ventilation for the first 6 min of the exercise test. An ANOVA showed a significant condition effect for both VO_2 (p = 0.009) and V_E (p = 0.001) during submaximal workloads. The average for both variables was lower in the heliox condition (VO_2 = 2.77 (0.18) l/min; V_E = 68 (5) l/min) compared with the nitrox condition (VO_2 = 3.02 (0.19) l/min; V_E = 79 (5) l/min). The attenuation in V_E was attained through a reduction in tidal volume, which was significantly lower during the heliox trial than in the nitrox trial at all submaximal time workloads (p = 0.011), whereas the breathing frequency remained unchanged (p = 0.3). All submaximal ventilatory variables increased as a function of workload (p<0.001), but there was no condition×time interaction for VO_2 and V_E.

Ratings of perceived exertion

We found no difference in the ratings of perceived exertion for either RPE_{15} (p = 0.8) or CR_{10} (p = 0.6) between trials, and both variables increased as a function of workload (p<0.001) (fig 3).

DISCUSSION

The main finding of this study was that substituting helium for nitrogen in the hyperoxic ambient air did not improve the maximal performance of exercise of trained cyclists during an incremental exercise test to exhaustion. This finding is contrary to results from most previous studies that have evaluated the effects of breathing a lighter gas on performance of exercise.[9 12 25] Furthermore, the perceived ventilatory effort was not

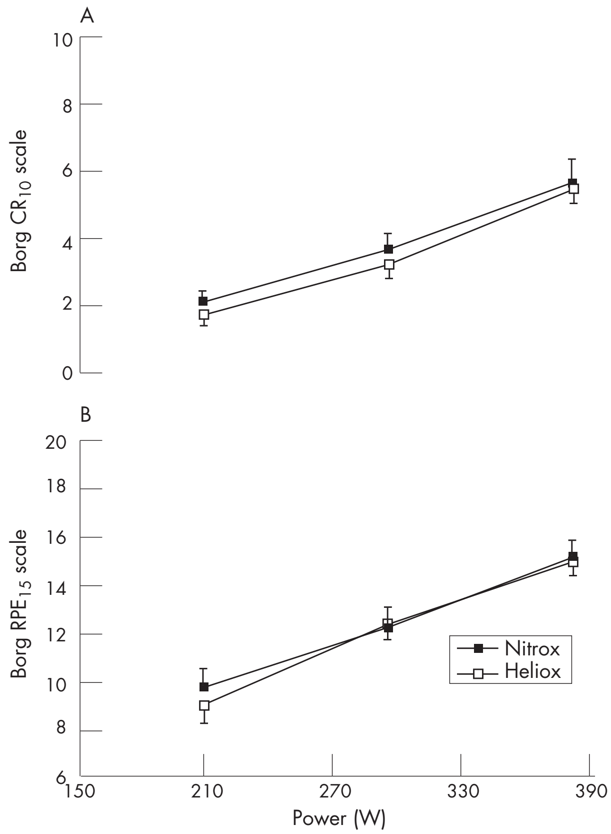

Figure 3 Mean (standard error) data for rating of perceived effort for localised respiratory exertion (A, Category-Ratio Scale (CR_{10})) and general whole-body exertion (B, rating of perceived exertion (RPE_{15})) during maximal incremental exercise performed in a sealed chamber under conditions of 30% O_2:70% N_2 (nitrox) and 30% O_2:70% He (heliox).

significantly attenuated when subjects breathed heliox. Thus, although the work of the respiratory muscles was potentially reduced by breathing a gas with a density of one fifth and a viscosity 1.12 times greater than the nitrox air,[26] the sensation of the effort of breathing was not reduced.

Babb[25] previously reported that the work of breathing is not altered when the density of the inspired air is reduced, as ventilatory volume was increased at submaximum workloads when heliox was breathed; however, in this study, minute ventilation was depressed at submaximum workloads (fig 2). A likely explanation for this discrepancy is the enormous difference in subject samples between the studies. A prerequisite for inclusion into Babb's study was pathological air flow limitation, whereas our subjects were extremely well-trained, healthy people. Therefore, breathing a lighter gas probably exerts a separate effect in populations that experience restricted breathing conditions. It seems logical that for people who have air flow limitations, and who therefore experience an attenuated ventilatory volume, breathing a lighter gas will improve their ventilation towards normal—that is, the ventilatory volume will increase. Certainly, Puente-Maestu *et al*[27] showed that a reduction in tidal volume is the limiter to exercise tolerance in patients with chronic obstructive pulmonary disease (COPD). Eves *et al*[22] previously showed that in patients with COPD, the submaximal tidal volume is increased when patients breathe a heliox gas mixture, but does not change when the patients breathe a hyperoxic gas even though both gas mixtures improve exercise tolerance to the same extent. This suggests that the mechanisms through which heliox and hyperoxia improve performance are different, a postulate that is supported by their observation that a hyperoxic heliox mixture exhibits a performance improvement effect greater than either hyperoxia or normoxic heliox individually.

In healthy people whose ventilation is compromised through hypobaric exposure, the supplementation of helium for nitrogen in the ambient air in hypobaric conditions has a similar effect to the COPD studies of increasing submaximal ventilation towards normobaric values through an increase in tidal volume.[28] Furthermore Esposito and Ferretti[12] reported that VO_2max and peak power were improved in hypoxic conditions when a heliox gas was inspired; however, they did not find any difference in either VO_2max or peak power when heliox was substituted in normoxic conditions. Interestingly, however, maximal expired and maximal alveolar ventilation were increased in both hypoxia and normoxia when heliox was substituted for nitrox. In people who have no pathological limitations to their ventilation, an effect of inspiring a less dense gas on respiratory work or ventilatory dynamics may be to reduce tidal volume at submaximal workloads. A lower ventilation and oxygen uptake at submaximum workloads, such as that observed in our study, implies superior gas exchange and unchanged airway resistance—that is, a lower ventilation is required to deliver oxygen, thus oxygen uptake is lower. Interestingly, the reduction in mean oxygen consumption at submaximum workloads observed during the heliox trial (about 8%) is similar to the oxygen cost that has been determined for breathing normal air during exercise (4.6–10%).[29] Although there was a reduction in submaximal V_E, the perceived ventilatory effort remained similar between trials. This can probably be explained by the fact that the reduction in V_E was attained through a reduced tidal volume and not a change in the breathing frequency. A change in the rate of breathing is the respiratory variable that has been associated with the perception of dyspnoea.[27]

Our study differed from other studies that have looked at maximal exercise capacity in healthy subjects breathing a heliox gas[9 12] in two important ways: (1) our subjects were highly trained cyclists and (2) our subjects inspired a hyperoxic gas mixture. Esposito and Ferretti[12] and Powers *et al*[9] reported an increase in maximal minute ventilation while breathing a heliox mixture, but Powers *et al* only reported an increase in VO_2max and workload under normoxic conditions. We have previously alluded to the fact that the effects of breathing a heliox gas may be twofold: an improved ventilatory capacity and improved ventilatory dynamics. With regard to the improved ventilatory capacity, the subjects in our study are accustomed to working close to their maximal capacity and therefore their respiratory system would be trained to cope with the volume of air that is moved in and out of the lungs at peak workloads. However, in less well-trained people, the respiratory system would be unaccustomed to the ventilatory volumes, especially at the higher workloads (which might explain why Powers *et al* and Esposito and Ferretti only noted differences in submaximal V_E at higher

Table 1 Measured mean arterial oxygen pressure and mean arterial oxygen saturation during maximal exercise in a study performed in the same chamber as those in this study[31]

	Rest		Peak exercise	
Condition	p_aO_2 (mm Hg)	s_aO_2 (%)	p_aO_2 (mm Hg)	s_aO_2 (%)
21%	111	98.6	94	94
30%	223	99.3	203	98.9

p_aO_2, mean arterial oxygen pressure; s_aO_2, mean arterial oxygen saturation.

What is already known on this topic

- Breathing a heliox mixture improves exercise tolerance in hypoxic conditions and in patients with COPD.
- The performance benefits derived from breathing a lighter gas have been associated with both a decrease in the sensation of ventilatory effort and an enhancement of arterial blood saturation.

What this study adds

- Breathing helium does not improve maximal performance when arterial blood saturation is maintained in trained athletes.
- Also, although submaximal tidal volume is attenuated when breathing heliox, the breathing frequency is maintained and, consequently, so too is the sensation of respiratory effort.

workloads) and therefore were not able to attain their functional maximal ventilation while breathing nitrox gas. However, as in the case of subjects with restricted breathing, heliox allowed them to ventilate closer to their maximal volume.

Additionally, we argue that the effects of the improved pulmonary gas exchange while breathing heliox, evidenced in this study by the lower submaximal ventilation, would have been even more pronounced had the exercise not been conducted in hyperoxic conditions. This argument is indirectly supported by Esposito and Ferretti,[12] who observed significantly improved maximal alveolar ventilation when heliox was inspired under hypoxic conditions as compared with normoxic conditions. Although alveolar ventilation did improve in normoxic conditions, it was to a lesser extent, and not statistically significant. Therefore, seemingly, breathing helium may be beneficial to improve work capacity in subjects who have respiratory pathologies or are not habituated to high ventilatory volumes, as well as in conditions of low inspired oxygen concentrations.

It is well documented that exercise-induced arterial hypoxaemia occurs at higher exercise intensities in some highly trained athletes.[30] Therefore, it could be argued that a compromised oxygen delivery to the working muscles limited the exercise capacity of these subjects before they reached the ventilatory volumes that would terminate exercise. However, it has been shown that the arterial pO_2 is better maintained during severe exercise when a heliox gas is inhaled compared with normal air.[9 19] Furthermore, Dempsey *et al*[19] and ourselves[31] have shown that the arterial desaturation associated with maximal work is completely counteracted when subjects breathe a hyperoxic gas mixture (24% and 30%, respectively; table 1).

Therefore, it seems unlikely that in this study maximal exercise capacity was limited by arterial desaturation in either condition.

The Bland–Altman plots for peak power, VO_2max and maximal V_E show the close limits of agreement between the trials for the peak power (−4.0% to 2.9%) compared with both VO_2max (−16.3% to 19.7%) and maximal V_E (−25.6% to 17.5%). These observations are similar to those of Laplaud *et al*,[32] who reported an interclass correlation of 1 for peak power using a similar protocol, and Kuipers *et al*,[33] who showed a coefficient of variation in peak power and VO_2max of 2.95–6.83% and 4.20–11.35%, respectively. Owing to the greater variability associated with the VO_2max and maximal V_E coupled with the variability previously reported for biological variables,[33] it seems doubtful that the termination of the exercise was due to a single physiological correlate but rather to a multivariable evaluation of integrated afferent feedback that probably includes mechanoreceptors, metaboreceptors and chemoreceptors.

SUMMARY

Conducting this study in hyperoxic conditions controlled for the confounding effect of exercise-induced arterial hypoxaemia during maximal exercise; therefore, any effects are attributable directly to the altered density of the inspired gas. Inspiring a less dense hyperoxic ambient gas does not improve the short-duration maximal exercise capacity of trained athletes, nor does it alter the perceived effort of breathing as measured by the Borg CR_{10} scale. However, the submaximal tidal volume was attenuated in the heliox trial, which was manifest in lower submaximal minute ventilation. This was matched by a concomitant reduction in the submaximal oxygen uptake. The reduction in both minute ventilation and oxygen consumption suggests an improved gas exchange during the heliox trial. Also, the extent to which the oxygen uptake was reduced is comparable to a reduction in the oxygen cost of ventilation. There does seem to be a potential role for heliox in improving performance in populations with impaired respiratory capacity or who are unused to high ventilatory volumes, as well as during maximal work in hypoxic conditions.

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COMMENTARY

This paper provides relevant data on furthering our understanding of cardiovascular dynamics during exercise, which may well impact on sporting performance and have clinical significance.

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Professor Mark Batt, BSc MB BChir MRCGP DM FFSEM FACSM, is a consultant in sport and exercise medicine at The Centre for Sports Medicine, University Hospitals NHS Trust, Nottingham. He has a busy NHS practice and is physician for The English Institute of Sport.

He graduated from Cambridge University Medical School in 1984 and trained in family medicine. He obtained a diploma in sports medicine from the University of London in 1991 and completed a fellowship in sports medicine at the University of California, Davis (UCD) in 1993. The next two years were spent as a faculty member in Family Medicine at UCD and as a team physician at the University of California, Berkeley.

Since 1995, he has been in Nottingham as a consultant/senior lecturer in sport and exercise medicine at the Queens Medical Centre: appointed special professor in 2004. He is currently clinical director for trauma and orthopaedics. He acts as clinical advisor for the Nottingham MSc/diploma courses in sports medicine. He serves or served as a consultant for The England and Wales Cricket Board, The Rugby Football League, British Gymnastics, The English Institute of Sport and The Wimbledon Tennis Championships. He is vice-chairman of the Faculty of Sport and Exercise Medicine and chaired the work-group that produced the case for sport and exercise medicine as a specialty of medicine. He is chairman of the newly created Specialist Advisory Committee in Sport and Exercise Medicine.

His research interests include: overuse injuries, particularly groin, low back, lower leg pain (shin splints and stress fractures); tendon disease; and exercise in the workplace.

He is married with two children. He enjoys a variety of sports, outdoor pursuits and gardening, none of which he does tremendously well!

Figure 1 Mark Batt.

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The effect of breathing an ambient low-density, hyperoxic gas on the perceived effort of breathing and maximal performance of exercise in well-trained athletes

L Ansley, D Petersen, A Thomas, et al.

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