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Br. J. Sports Med. 2008;42;877-881; originally published online 10 Dec 2007;
doi:10.1136/bjsm.2007.042960

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Accepted 20 November 2007
Published Online First 7 December 2007

ABSTRACT

Background: Aircraft cabins are pressurised to maximum effective altitudes of 2440 metres, resulting in significant decline in oxygen saturation in crew and passengers. This effect has not been studied in athletes.

Objective: To investigate the degree of decline in oxygen saturation in athletes during long-haul flights.

Methods: A prospective cross-sectional study. National-level athletes were recruited. Oxygen saturation and heart rate were measured with a pulse oximeter at sea level before departure, at 3 and 7 hours into the flight, and again after arrival at sea level. Aircraft cabin pressure and altitude, cabin fraction of inspired oxygen and true altitude were also recorded.

Results: 45 athletes and 18 healthy staff aged between 17 and 70 years were studied on 10 long-haul flights. Oxygen saturation levels declined significantly after 3 hours and 7 hours (3–4%), compared with sea level values. There was an associated drop in cabin pressure and fraction of inspired oxygen, and an increase in cabin altitude.

Conclusions: Oxygen saturation declines significantly in athletes during long-haul commercial flights, in response to reduced cabin pressure. This may be relevant for altitude acclimatisation planning by athletes, as the time spent on the plane should be considered time already spent at altitude, with associated physiological changes. For flights of 10–13 hours in duration, it will be difficult to arrive on the day of competition to avoid the influence of these changes, as is often suggested by coaches.

Commercial airline travel is steadily increasing among the general population, as well as sporting teams. With aircraft flying over long distances (up to 18 hours non-stop) and at high altitudes (up to 11 887 metres (39 000 feet)), airliner cabins have to be pressurised to protect passengers from the consequences of exposure to extremely low barometric pressures. However, owing to structural and economic constraints, cabins are not pressurised to sea level.[1] Regulatory agencies have established safety guidelines that generally allow airliners to pressurise cabins to a maximum altitude of 2440 metres (8000 feet).[2] This may be exceeded in emergencies. Average cabin pressures are 1520–1828 metres (5000–6000 feet), which is equivalent to an inspired oxygen pressure (PO_2) of 132–127 mm Hg.[3,4] Passengers on long-haul flights are therefore exposed to reduced oxygen pressure for periods of up to 18 hours at a time. Several authors have reported a decrease in oxygen saturation levels in passengers and crew.[5–9] The groups studied included airline crew, children, cardiorespiratory patients and the general passenger population. However, no studies have measured the response in elite athletes. The relevance for athletes is that the effective altitude in the aircraft cabin is similar to the altitudes often encountered in sporting competitions. This may have an impact on altitude acclimatisation planning, as the hours spent on a long-haul flight may have to be considered as time already spent at the competition altitude, with associated physiological changes. The purpose of this study was to investigate the degree of decline in oxygen saturation in athletes during long-haul flights and to consider the implications for acclimatisation planning.

METHODS

Athletes who were due to embark on international flights were recruited. The inclusion criteria were: age >16 years and playing in a national or international level senior or age-group team, involving aerobic sports. The exclusion criteria were: severe cardiorespiratory disease, current smoker, recent (<1 month) exposure to altitude >1000 metres, intermittent hypoxic training and active upper respiratory infections. Ethics approval for this study was obtained from the human participants ethics committee of the University of Auckland. Oxygen saturation and heart rates were measured with a pulse oximeter (Nellcor NBP-40) at sea level before the flight. The measurements were repeated at 3 hours and 7 hours into the flight, and finally after arrival, again at sea level. Aircraft cabin pressure and altitude, cabin fraction of inspired oxygen and true cruising altitude were also recorded.

Statistical analysis

To ensure each subject contributed equally, the data from multi-leg journeys were averaged for each subject before analysis.

The differences in oxygen saturation and pulse rate were analysed using analysis of variance (ANOVA) with posthoc tests of significance (Tamhane and Tukey honestly significant difference test). Correlations were assessed using the Pearson correlation coefficient.

RESULTS

In total, 45 athletes and 18 healthy staff were recruited to the study and during 10 flights, 171 individual sets of measurements were taken. Two flights were 3 hours in duration and 8 flights were ⩾10 hours. The average age of all participants was 30.62 (95% CI 28.35 to 32.88). The age of the athletes was 26.20 (25.26 to 27.23) and the age of the management team was 41.56 (36.83 to 46.28) Cruising altitude ranged from 9554 to 12500 metres above sea level and measured cabin

Table 1 Average values for all subjects (mean (SD))

	Measurements			
	Pre-flight	3 hours	7 hours	Destination
SpO_2	97.45 (0.97)	93.64 (1.26)	93.95 (1.45)	97.27 (1.04)
Pulse rate	70.53 (7.41)	72.32 (6.99)	70.68 (7.27)	70.34 (7.38/)

SpO_2, oxygen saturation.
Data are mean (SD).

altitude (as determined by measured pressure) ranged from 1200 to 2300 metres above seal level with a mean cabin altitude of 1689 metres.

Oxygen saturation decreased significantly from the pre-flight measurement to the 3 hour and 7 hour measurements. The oxygen saturation at destination was the same as pre-flight (table 1, fig 1).

Posthoc testing showed that pre-flight and destination oxygen saturations were significantly ($p<0.001$) different from the 3 hour and 7 hour in-flight measurements. The decrease in oxygen saturation was similar at both 3 and 7 hours for each individual but was not associated with age or athlete status (fig 2). There was no significant change in the pulse rate observed at the different measurement times (table 1, fig 3).

There was no significant association between the cabin altitude at which measurements were made and the oxygen saturation recorded (fig 4).

DISCUSSION

In-flight oxygen saturation decline in various groups

The current study is the first to our knowledge to measure the decline in oxygen saturation experienced by athletes during long-haul flights. Similar findings have also been reported in other population groups. The study of Cottrell *et al*, which continuously monitored oxygen saturation in 42 healthy airline crew members, found significant levels of desaturation (SaO_2 80–93%, with a mean of 88.6%) at cabin altitudes of (1828–2606 metres (6000–8550 feet) (mean 2320 metres (7610 feet)), compared with pre-flight saturation (mean 97%).[5] Heart rates were not reported. The authors reported large variations between individuals and commented on the fact that crew members would be expected to be healthier and fitter than the general travelling public and therefore less susceptible to the effects of desaturation. Bendrick *et al* published a similar study in the same year, but the study group consisted of 24 ambulatory aeromedical evacuation patients with known or suspected ischaemic heart disease.[7] That group reported a mean saturation decrease of 5.5% (95% CI 4.5 to 6.4) at a mean cabin altitude of 2103 metres (6900 feet). Three patients were given supplemental oxygen because their in-flight oximeter reading was consistently <90%. However, the mean decrease in oxygen saturation was only slightly more severe than the decrease that would be expected of healthy individuals at a corresponding altitude. The authors also concluded that oxygen saturation values could not be reliably predicted by in-flight cabin altitude. In 2000, the House of Lords Select Committee on Science and Technology reviewed the literature on air travel and health. The committee came to the conclusion that modern aircraft tended to fly at higher cabin altitudes and that there was insufficient knowledge about the effect of oxygen desaturation on the travelling public.[1] A specific recommendation was made that further investigation, using non-invasive oximetry, should be conducted into the in-flight oxygen saturation of a wide range of crew members and passengers.

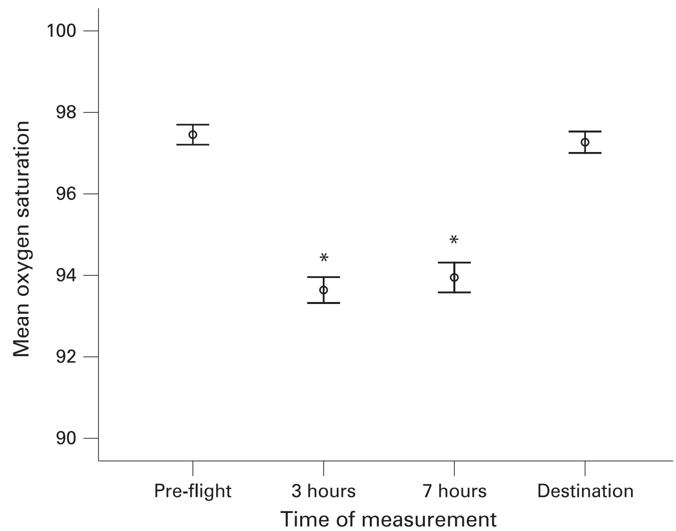

Figure 1 Mean oxygen saturation obtained by pulse oximetry (error bars represent 95% CI of the mean).

This was followed by a statement by the British Thoracic Society containing guidelines on managing patients with lung disease planning air travel.[10] Recommendations were based on the fact that with the current regulations, cabin altitudes of up to 2438 metres (8000 feet) may be reached, and even exceeded in emergencies. In healthy passengers the arterial oxygen tension (PaO_2) could therefore be expected to fall to 53–64 mm Hg, which is equivalent to oxygen saturation (SpO_2) of 85–91%. The concern was that altitude exposure may exacerbate hypoxaemia, particularly in passengers with chronic lung disease who are hypoxaemic at sea level.

Several studies investigating this effect in various groups were subsequently published. Lee *et al* documented decreases in oxygen saturation (mean of 94.4% at cruising altitude, compared with 98.5% at sea level), and significant increases in heart rate (108 beats/minute at altitude compared with 100 beats/minute at sea level) in 80 healthy children (maximum

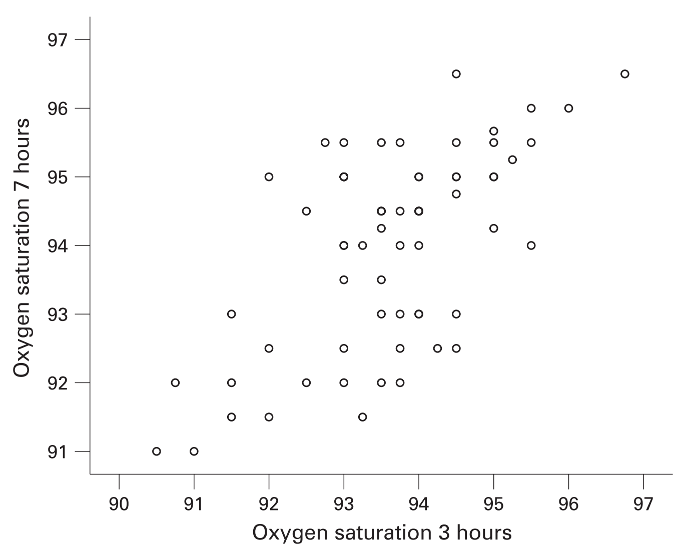

Figure 2 Correlation between oxygen saturation measured in subjects at 3 hours and 7 hours in flight. The decrease in saturation was not random; there was significant correlation between the saturation at 3 and 7 hours in flight (Pearson correlation coefficient 0.780, $p<0.01$).

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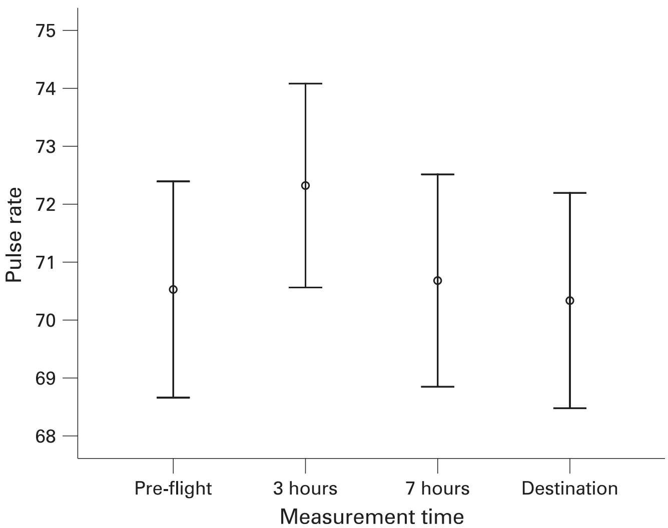

Figure 3 Pulse rate (error bars represent 95% CI for mean).

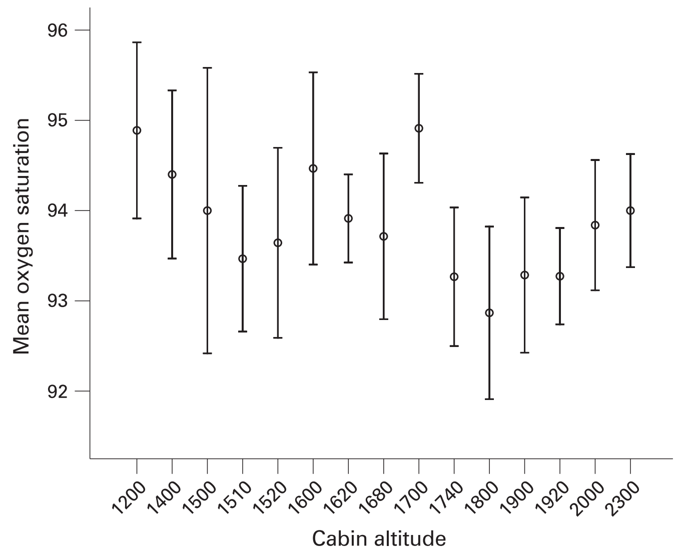

Figure 4 Measured oxygen saturations at different cabin altitude (error bars represent the 95% CI for the mean).

cabin altitude reached was 2222 metres, with a mean of 2034 metres at 3 hours and 2087 metres at 7 hours).[6] Seccombe *et al* studied 25 patients with chronic lung disease (chronic obstructive lung disease (COPD) and interstitial lung disease). The authors used a simulated environment, with subjects breathing room air and a hypoxic gas mixture, equivalent to 15% oxygen (similar to that expected at 2438 metres of altitude).[8] The authors found significant decreases in oxygen saturation levels (mean 95.7% and 96.5% in room air and 83.2% and 87% in 15% oxygen for the COPD group and the interstitial lung disease group, respectively). The saturation levels decreased even further when a 50 metre walking task was added under hypoxic conditions ($SaO_2 = 76.8\%$ and 79.5% respectively); only eight subjects managed to complete the walking task. Interestingly, 52% of the subjects had flown in the previous 2 years, half of whom had walked to the lavatory during the flight, and 54% were planning to fly in the near future. Muhm developed a statistical model for predicting oxygen saturation in commercial aircraft cabins, using age, sea level PaO_2, sea level carbon dioxide tension ($PaCO_2$) and cabin altitude as predictive variables.[11] He suggested that a substantial number of passengers with obstructive airway disease and those >65 years of age will develop in-flight hypoxia severe enough to warrant the use of supplemental oxygen. More recently, Humphreys *et al* investigated the effect of high-altitude commercial air travel on oxygen saturation in 84 passengers aged between 1 and 78 years, without history of cardiorespiratory disease.[9] Once again, significant decreases in oxygen saturation levels were recorded (mean 93% at cruising altitude, compared with 97% at sea level). There was no significant change in heart rate. Cabin altitudes were not reported in this study.

It seems that the reported fall in oxygen saturation has been generally less severe in healthy subjects than in those with cardiopulmonary compromise. It is therefore not surprising that the oxygen desaturation in the elite athletes in our study was only of a moderate degree. It is interesting to note that there were no significant changes in pulse rates. This may be explained by the fact that aerobic athletes are expected to have well-developed mechanisms for facilitating oxygen transport and utilisation under hypoxic conditions at the muscular level, with a resultant smaller compensatory effect on the cardiovascular system. However, even modest reductions in oxygen saturation levels still reflect acute exposure to hypoxia at altitude, equivalent to that experienced by athletes when arriving for competition at a similar altitude. In the case of our study, the mean altitude was 1800 metres, which is similar to that of Johannesburg (1800 metres, host for the 2010 Soccer World Cup), and the maximum altitude was 2300 metres, slightly higher than that of Mexico City (2259 metres, host to the Summer Olympic Games in 1968). It was also only 200 metres lower than the altitude identified by the FIFA Medical Committee in May 2007 as an unsafe altitude for football games in their controversial "altitude ban" (this altitude limit was eventually increased to 3000 metres in July 2007, amid differing medical opinions on the physiological effects of playing at these altitudes). Competition at these altitudes is generally considered to affect performance and usually require acclimatisation planning.

Competing at moderate altitude

The announcement in 1964 of Mexico City as the host city for the summer Olympic Games 4 years later became the stimulus for research into the effects of moderate altitude exposure on physiological and performance parameters of competing athletes.

The initial studies focused on VO_{2max} as the main determinant of performance, were not well controlled and did not result in clear conclusions. However, they did suggest that altitude exposure immediately resulted in a significant decline in both VO_{2max} and time trial performance in aerobic sports, that it required several weeks for this decline to normalise to sea level values and that there was significant variability in response between individuals and between different types of exercise.[12–14] Interestingly, such studies also suggested that VO_{2max} was not the only determinant of performance, as some time-trial performances remained reduced at altitude, even when VO_{2max} had returned to sea-level values.[13 14]

These findings were confirmed during the Games, and it was generally accepted that the performance of athletes participating in aerobic endurance events was adversely affected by altitude, whereas athletes involved in speed and anaerobic events were either unaffected or even performed better at altitude than at sea level.[15] Since then, the physiological effects of acute and chronic altitude exposure have been studied in depth and extensively documented, although our understanding of these processes is still incomplete and significant controversy regarding their implications still exists. One of the controversial issues that remains is the time required to achieve acclimatisation and consequently how long in advance of competition an athlete needs to arrive at that altitude.

The physiological effects of exposure to moderate altitude

The main stimulus for the immediate physiological changes experienced at altitude is the decreased pressure of inspired oxygen (FiO_2).[16] This is due to the fact that whereas the partial pressure of oxygen remains a constant percentage of atmospheric pressure at altitude (21%), the absolute pressure of oxygen is reduced proportional to the absolute atmospheric pressure. Therefore, at an altitude of 2000 metres, the partial pressure of oxygen is 124.9 mmHg for dry air, which corresponds to a pressure of inspired oxygen (PiO_2) of 115.1 mmHg.[17]

A complex cascade of adaptive physiological events to this hypoxic stimulus has been described and includes initially pulmonary, renal and cardiovascular and, eventually, haematological changes. The two most prominent acute responses are hyperventilation (via the hypoxic ventilatory response) and renal diuresis (via increased bicarbonate and fluid excretion).[18–20]

The hypoxic ventilatory response shows considerable variability among individuals and does not significantly affect the VO_{2max} at altitude.[19] However, it has been suggested that in combination with renal diuresis, it may result in dehydration, which may in turn affect performance significantly.[20 21] On the other hand, Parker has suggested that these changes (and the associated changes in acid–base balance) may in fact be advantageous, by maintaining the oxygen saturation of arterial blood (SaO_2) and therefore delivery of oxygen to the exercising muscle, which ultimately positively influences VO_{2max}.[21]

The cardiovascular changes to altitude include an initial increase in cardiac output, via an increase in heart rate, but within 2–8 days after ascent to altitude, the stroke volume decreases significantly and with it, the cardiac output.[22–25] These changes would suggest a significant decline in VO_{2max} and subsequently performance. It seems that these changes are more pronounced and therefore problematic at higher altitudes (⩾2500 metres) and in fact, some researchers have actually found a decrease in exercise heart rate at lower altitudes (1900 metres).[26] The exact time course and altitude required for these different responses, as well as the time required for eventual reversal of these changes, is still unclear.

Acute haematological changes include an increase in 2,3-diphosphoglycerate within red blood cells, which occurs within a few hours of ascent to high altitude.[27] This results in a rightwards shift of the oxyhaemoglobin dissociation curve, an increase in the P_{50} (oxygen pressure at 50% haemoglobin–oxygen saturation) value and an increase in the release of oxygen to the tissue. This adaptation should theoretically be advantageous to performance at altitude, but in a study by Mairlbaurl *et al*, performance capacity was decreased by 9% despite an increase in P_{50} values on the first day of ascent to an altitude of 2300 metres.[28]

Further, longer term changes associated with altitude exposure include increases in erythropoietin, red blood cell production and skeletal muscle adaptations, although the exact nature of the muscular metabolic changes is still unclear.[4 29 30] These could all be expected to improve performance, but the effects are not seen within the first few days after ascent. Eventually, acclimatisation occurs and there is a normalisation of heart rate, improved pulmonary perfusion, increased haemoglobin levels and improved cellular oxygen utilisation, all of which are beneficial for performance at both altitude and sea level.[31 32]

In summary, several studies have documented the immediate and delayed physiological effects of altitude exposure, but it is still unclear if the individual changes ultimately have a positive or negative effect on performance at altitude. More importantly, the time course for these changes has not been accurately determined.

Optimum time of arrival for competition at altitude

Owing to the controversies around the theoretical advantages and disadvantages of the immediate physiological changes experienced at altitude, there are no clear guidelines regarding altitude acclimatisation for athletes. Studies have persistently reported decreases in maximal oxygen uptake (VO_{2max}) and performance immediately after ascent to altitude.[14 15] The effect has been documented from an altitude of 1200 metres, with a subsequent rate of decline in VO_{2max} of 3% for every 300 metres, although declines have been measured at altitudes as low as 580 metres.[29–30 33–34] Performances in long-duration and aerobic exercise seem to be the most affected.[35] Although it is clear that acclimatisation does eventually occur, it is still unclear how much time is necessary for adaptation to be completed, as there are so many variables involved. Findings range from 24 hours to several months, depending on the outcome measures investigated.[36 37] It is also unclear what the optimum time of arrival for competition at altitude would be, and whether the detrimental effects of altitude could be avoided by competing before any definitive changes occur.

Daniels suggested after the 1964 Olympic Games in Mexico City that performance at altitude would be best either immediately upon arrival or after acclimatisation has occurred.[15] This concept was questioned in a recent study by Weston *et al*, when they reported significant detrimental effects of moderate altitude (1700 metres) on performance, with the most pronounced reductions occurring only 6 hours after arrival at altitude.[37] Some improvement in performance was noted at 18 hours and 47 hours after exposure, but no further improvements occurred after 47 hours. The authors concluded that travel to moderate altitude for competition should ideally occur as early as feasible.

Despite this lack of clear evidence-based guidelines, many athletes and coaches believe the acute effects of altitude are more severe on the second day after arrival at altitude and that acclimatisation requires several days to weeks to occur. For this reason, the current popular advice given to many athletes and sporting teams is to arrive either several days or weeks in advance, or shortly before sporting competition, ideally on the same day.[38–40] In fact, because of financial and time constraints, athletes will often aim to arrive at altitude in the morning on the day of competition, thereby avoiding spending prolonged time at that altitude. A literature review and internet-based search did not reveal any evidence that athletes, coaches or researchers consider the time spent in a commercial aircraft en route to the competition venue as time already spent at altitude.

Summary

Our results suggest that elite athletes experience a significant decrease in oxygen saturation for a prolonged time during long-haul flights. This is due to the hypoxic stimulus of mean cabin

What is already known on this topic

- Commercial airline travel results in significant in-flight decline in oxygen saturation in crew and passengers.
- Athletes often need to compete at altitudes similar to the effective altitudes experienced in airliner cabins.
- Although altitude acclimatisation changes have been studied extensively, the exact timing and impact of these changes on performance is still unclear.
- There is significant controversy regarding the timing of arrival for competition at altitude.

What this study adds

- Elite athletes also experience significant decline in oxygen saturation levels during commercial flights.
- It is biologically plausible that physiological changes of altitude acclimatisation may already have commenced whilst in-flight to competitions at altitude. This requires further research.
- Future guidelines regarding the optimum time of arrival for competition at moderate altitude need to consider the time spent on a long-haul flight as time already spent at altitude.

altitudes of 1800–2000 metres and is physiologically equivalent to arriving at altitude within the day of competition. It is biologically plausible that certain adaptive changes may already be initiated during this time. Further research will be required to determine whether these changes are indeed occurring and if so, whether they are advantageous or detrimental to performance.

We would suggest that any future guidelines regarding the optimum time of arrival for competition at moderate altitude need to consider the time spent on a long-haul flight as time already spent at altitude. Additionally, the current recommendation by many coaches to arrive on the day of competition needs to be revisited, not only because some studies seem to suggest that it may actually be detrimental to performance, but also because it may well be physiologically impossible to achieve after a long-haul flight.

Competing interests: None.

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