WORKING AT HIGH ALTITUDE: MEDICAL PROBLEMS, MISCONCEPTIONS, AND SOLUTIONS

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Abstract

Telescopes are being placed at increasingly high altitudes. The summit of Mauna Kea, Hawaii (altitude 4200 m) has been a popular site for some time, but more recently telescopes have been located on the Chajnantor plateau in north Chile at an altitude of 5050 m. This will also be the site of the multinational Atacama Large Millimeter Array. Other nearby sites up to 5800 m have been used for various instruments. Although remote observing is increasingly employed this is not always possible, and it will always be necessary to have some human beings at the sites. These altitudes can have serious effects on mental and physical performance and quality of sleep. The deleterious effects are reduced by the process of acclimatization but it is a misconception to argue that this returns mental and physical performance to normal. In fact fully acclimatized astronomers on the summit of Mauna Kea are so oxygen-deprived that if this was caused by lung disease at sea level they would be entitled to treatment by continuous oxygen therapy. All the medical effects of high altitude are caused by the low partial pressure of oxygen in the inspired air, and so the most effective way of improving human performance is to add supplementary oxygen. Recent technical advances allow this to be done very efficiently by oxygen enrichment of room air. The occupants of the room are generally unaware of the added oxygen but their mental and physical performance is significantly enhanced. Oxygen enrichment for altitudes of 5000 m and above should be mandatory and would also be helpful at more modest altitudes such as 4200 m.

1. Introduction

Increasingly, astronomers are setting up instruments and working at high altitudes. The low scale-height of water in the atmosphere, and the dramatically reduced precipitable water burden at high altitudes improves atmospheric transmission dramatically in critical wavelength bands. One of the best known sites is Mauna Kea, Hawaii where the altitude of the summit is 4200 m and there are a number of telescopes on or near the summit. Recently there has been much activity in north Chile in the Chajnantor region east of San Pedro de Atacama. Here there is an extensive plateau at an altitude of about 5050 m and this can be accessed most days of the year by a road from San Pedro de Atacama (altitude 2440 m). A group from the California Institute of Technology has been operating the Cosmic Background Imager (CBI) there since August 1999. The site will also be used by the multinational Atacama Large Millimeter Array (ALMA). Nearby a German group has installed a telescope near the CBI at an altitude of 5050 m and there is a Japanese telescope at the slightly lower altitude of 4800 m. Even higher sites on nearby extinct volcanoes have been investigated, and altitudes up to 5800 m have been used occasionally. Groups from Princeton and the University of Pennsylvania have operated the Mobile Anisotropy Telescope (MAT) near this altitude successfully on three occasions for periods of up to several months.

These altitudes have many important effects on the human body and there is a large literature on the subject[1,2]. Several articles have been written specifically for astronomers[3-7]. However there have been a number of important advances in the last five years. In addition some misconceptions about the medical effects of high altitude have developed in some members of the astronomy community. One of these is that acclimatization to high altitude fully protects the individual from the deleterious effects of the low oxygen. This is a serious fallacy and is discussed in more detail below. A major recent advance is improvements in technology that allow economical oxygen enrichment of the working spaces for astronomers at high altitude. Although there is a curious prejudice against this innovation in some quarters, all the evidence suggests that it is an important advance for people who have to work at high altitude, leading to substantial improvement in personnel safety, and more cost-effective operations.

Of course the fact that telescopes are sited at high altitude does not necessarily mean that the observers are there. In fact the technology of remote observing is now very sophisticated. Nevertheless it is certainly necessary to have humans at the observatory site while the telescope is being built and tested, and in most instances some staff will be required at the site. Therefore human factors at high altitude will always be important.

This brief review will first summarize how the oxygen deprivation at high altitude affects the human body. Then the important topics of acclimatization to high altitude, and the common high-altitude diseases will be briefly covered. Finally methods of combatting the oxygen deprivation of high altitude will be considered.

2. Why High Altitude Affects the Human Body

High altitude impairs human function because of the oxygen deprivation. Of course other factors such as cold and high winds may be present but these can be negated by appropriate protection. The reduction in oxygen is best described by the fall in inspired partial pressure of oxygen (PO_2). As altitude increases, barometric pressure falls though here it is worth mentioning that for most locations of interest to astronomers (for example, Mauna Kea and north Chile) the Standard Atmosphere[8] is not applicable. The reason is that these locations are at low latitudes where the barometric pressure for a given altitude is higher than predicted from the Standard Atmosphere. As an example, at an altitude of 5800 m near Chajnantor the Standard Atmosphere predicts a barometric pressure of 363.5 torr (485 mb) whereas the actual pressure is close to 379.0 torr (505 mb). This difference is significant from a physiological point of view and, for example, represents a change of altitude of over 300 m.

Physiologists always calculate the inspired P_{O_2} because that is the partial pressure of oxygen actually available to the body. When air is inspired it is warmed and saturated with water vapor at the body temperature of 37°C and therefore the water vapor pressure is 47 torr. This is irrespective of altitude. Therefore the inspired P_{O_2} is given by $P_{IO_2} = 0.2093 (P_B - 47)$ where P_B is the barometric pressure. The inspired P_{O_2} at sea level, the University of California White Mountain Research Station (altitude 3800 m), Mauna Kea (altitude 4200 m), Chajnantor (altitude 5050 m) and a nearby peak (altitude 5800 m) are shown in Table I.

It can be seen that at Chajnantor the inspired P_{O_2} is only about 52% of the sea level value. The table is perhaps misleading in that it shows that the difference of P_{O_2} between Mauna Kea and Chajnantor is only 7% of the sea level value, and that between Chajnantor and the nearby peak at 5800 m is only about 5% of the sea level value. However the physiological effects of this oxygen reduction are very nonlinear. There is a world of difference between the physiological effects of hypoxia at Chajnantor and Mauna Kea, and again a very large difference between 5800 m and Chajnantor (see later).

3. Effects of High Altitude on Human Performance

The medical effects of high altitude are legion. However in the present context they are best described under three headings.

3.1. Mental Performance

Most people who have worked at altitudes over 4000 m state that mental ability is impaired. They recognize an increased number of arithmetical errors, reduced attention span, increased fatigue, impaired short-term memory, and increased difficulty in making decisions. However it has proved to be very difficult to quantitate impairment of mental function. This was recognized eighty years ago by the British physiologist Joseph Barcroft when he was reporting on his experiences at Cerro de Pasco, Peru (altitude 4330 m) and wrote:

> ...judged by the ordinary standards of efficiency in laboratory work, we were in an obviously lower category at Cerro that at the sea level. By a curious paradox this was most apparent when it was being least tested, for perhaps what we suffered from chiefly was the difficulty of maintaining concentration. When we knew we were undergoing a test, our concentration could by an effort be maintained over the length of time taken for the test, but under ordinary circumstances it would lapse. It is, perhaps, characteristic that, whilst each individual mental test was done as rapidly at Cerro as at the sea level, the performance of the series took nearly twice as long for its accomplishment. Time was wasted there in trivialities and 'bungling', which would not take place at sea level[9].

In other words, most intelligent competitive people when faced with a test of mental function are determined to do the best they can, and perform very well in the short term. However this performance is not typical of that during the full working day.

Nevertheless McFarland has reported data on mental performance of unacclimatized individuals at altitudes from 2500 to 5000 m and these are shown in Table II. The difficulties of making these measurements are so great that the emphasis should be on the pattern of changes rather than the individual numbers. Other investigators, for example Sharma and colleagues [10] have shown impairment of hand-eye coordination in acclimatized subjects at an altitude of 4000 m where their performance was only 63% of sea level after one month and this improved to 83%

after several months. In all these tests the "learning effect," that is the ability to perform better when the test is repeated on a number of occasions, can be important and is difficult to take into account. Not all investigators have reported impairment of mental ability at altitudes of 4000 m. For example, Forster[4] measured numeric memory in shift workers in the U.K. Infrared Telescope (UKIRT) at Mauna Kea and found that this was reduced to 88% of its sea level value on the first day of work at 4200 m, but improved over the next few days so that by the fifth day there was no significant difference between altitude and sea level. Here the effects of acclimatization are important (see below) but again it is difficult to rule out the learning effect.

3.2. Physical Performance

The rate at which humans can perform physical work (power output) depends on the amount of oxygen available to the body, so it is not surprising that as the altitude increases, maximal oxygen uptake falls. There is a large literature on this topic and at the altitude of Mauna Kea (4200 m) the power output of the body is reduced to about 70% of its sea level value. At the altitude of Chajnantor (5050 m) power output drops to about 60% of the sea level value, and there is a further fall to about 50% at an altitude of 5800 m. Although astronomers working at a high altitude site will not often be called upon to exert maximum effort, the limitations in the amount of physical work that can be done will be obvious.

Muscular exertion at high altitude is accompanied by very high levels of ventilation, that is the product of rate and depth of breathing. As a result, people working at high altitude pant and the resulting shortness of breath is often unpleasant. This panting will often continue for several minutes after performing a heavy task. In fact even a small increase in activity, for example sitting up in bed, at an altitude of 5800 m may cause panting for two or three minutes.

Just as important as the limited power output at high altitude is the great increase in fatigue that follows several hours' work. This is difficult to quantitate but people working at altitudes of 5050 or particularly at 5800 m will generally find it impossible to do a full day's physical work.

3.3. Sleep

One of the most unpleasant features of going to high altitude is difficulties with sleeping. Indeed many people notice this at very modest altitudes such as 2500 to 3000 m at ski resorts. Typically people complain that they wake frequently, have unpleasant dreams, and do not feel refreshed in the morning. An important causative factor is "periodic breathing" during which the breathing waxes and wanes with typical cycles of ten to fifteen seconds. Periods of no breathing at all (apnea) lasting up to five or ten seconds may occur, and it is believed that the low oxygen levels in the blood following apneic periods may account for some of the arousals. Many measurements have been made during sleep at high altitude and these show large fluctuations in the concentration of oxygen in the arterial blood caused by the waxing and waning of breathing. Electroencephalographic studies confirm that the quality of sleep is impaired at high altitude. Mountain climbers often adopt the policy of climbing high and sleeping low in order to reduce the difficulties of sleeping.

4. ACCLIMATIZATION

Fortunately the human body has the ability to adapt to the oxygen deprivation of high altitude to some extent, a process known as acclimatization (or acclimation). In fact physiologists often use high-altitude acclimatization as one of the best examples of the body's response to a stressful environment.

The two most obvious features of high-altitude acclimatization are the increase in breathing (hyperventilation) and the increase in concentration of red blood cells (polycythemia). There are other less obvious features including an increased concentration of capillaries in some body tissues, and changes of oxidative enzymes in the cells that enhance the ability of the tissues to operate in an oxygen-deprived environment.

By far the most important feature of acclimatization is hyperventilation which is brought about by an increase in both the rate and depth of breathing. As examples, an acclimatized person at an altitude of 4200 m will have his or her ventilation increased by 15% while an acclimatized subject at an altitude of 5800 m will have an increase of over 70%. It is this large increase in ventilation that is responsible for the panting and sensation of shortness of breath on exercise.

The increase in ventilation is brought about by stimulation of sensors (chemoreceptors) that respond to the low partial pressure of oxygen in the arterial blood. The advantage of hyperventilation is that it raises the PO_2 in the air in the depths of the lung (alveolar gas) and thus counters the oxygen deprivation of the environment to some extent. The degree to which this is effective is discussed below. When an individual goes to high altitude, the hyperventilation gradually increases over the course of several days and this important feature of the acclimatization process is essentially complete in ten days.

The other well-known feature of acclimatization is an increase in the concentration of red cells in the blood (polycythemia). However the value of this process is very limited. First it takes several weeks to develop and probably two or three months to reach its maximum value. It is true that newcomers to high altitude often show an increase in red blood cell concentration within a day or so but this is solely caused by dehydration and therefore concentration of the blood which is very common at high altitude. All the evidence suggests that in the context of astronomers working at high altitude, the increase in red cell concentration is a very minor advantage at high altitude. Interestingly some people who spend many months at very high altitudes, for example 5800 m, develop such high levels of red cell concentration that these are thought to be disadvantageous because the great cellularity of the blood affects its flow in peripheral capillaries and consequently interferes with oxygen unloading [2]. Polycythemia also increases the likelihood of deep vein thrombosis.

4.1. Effectiveness of Acclimatization

As indicated above, the most important feature of acclimatization is the hyperventilation which increases the P_{O_2} and reduces the P_{CO_2} of the alveolar gas. The efficacy of acclimatization at various altitudes is shown in Figure 1. The horizontal broken line at a P_{O_2} of 100 torr shows the alveolar P_{O_2} at sea level. The data for the lines indicating the alveolar P_{O_2} for acute exposure to high altitude (that is, with no acclimatization) and for full acclimatization come from Rahn and Otis[11]. It can be seen that useful gains in the alveolar P_{O_2} of between 5 and 10 torr occur at all the altitudes of interest. However both the alveolar P_{O_2} for acute exposure and full acclimatization fall rapidly as altitude increases. Of course the reason for this is the fall in inspired P_{O_2} which is also shown in the figure. Note that at the summit of Mauna Kea the alveolar P_{O_2} for acute exposure is about 45 torr but this increases to about 53 torr if the subject is fully acclimatized. For Chajnantor (altitude 5050 m) the numbers are about 39 and 47 torr, respectively, and for the highest peak at altitude 5800 m, the values are about 35 and 43 torr, respectively. It should be remembered that full acclimatization requires continuous residence at the altitude of about ten days.

4.2. Misconceptions about the Value of Acclimatization

Although as pointed out above, the hyperventilation of acclimatization ameliorates the hypoxia of high altitude to some extent, it is very important to emphasize that the oxygen levels in the alveolar gas, arterial blood and body tissues are still very low. There seems to be a misconception among some astronomers who argue that acclimatization to high altitude reverses all of its deleterious effects. This is a dangerous error.

One way of emphasizing this is to compare the oxygen deprivation of astronomers at high altitude with that seen in patients with severe lung disease. Figure 1 shows that the threshold for administering continuous oxygen therapy to patients who have chronic obstructive pulmonary disease (a very common condition including chronic bronchitis and emphysema) is a P_{O_2} of 55 torr. Actually this is the arterial P_{O_2} because the alveolar value is difficult to measure in the presence of severe lung disease. In normal subjects at high altitude the arterial P_{O_2} is about 2-5 torr below the alveolar value. However if we assume the best case, that is that the alveolar and arterial P_{O_2} are the same, some surprising results emerge from Figure 1. This shows that astronomers who are fully acclimatized on the summit of Mauna Kea have an alveolar P_{O_2} of slightly less than the threshold for continuous oxygen therapy. In other words, if these people had the same degree of oxygen deprivation at sea level caused by lung disease, they would be entitled to continuous oxygen therapy under Medicare (U.S. federal health insurance program). The same criterion is used by the N.H.S. in the U.K. Moreover extensive studies have now shown that continuous oxygen therapy in these patients who have an arterial P_{O_2} of less than 55 torr results in improvements in neuropsychological function measured when they are breathing air[12]. This demonstration of the value of continuous oxygen therapy in patients with severe hypoxia explains the large number of oxygen concentrators in patients' homes. The studies also emphasize the extent to which even fully acclimatized astronomers on the summit of Mauna Kea are impaired by the oxygen deprivation. It makes little sense to argue that these people would not benefit from supplementary oxygen.

5. High-Altitude Diseases

Only a brief discussion of these is given here because they are fully covered in major medical textbooks[2] and smaller books designed for climbers and trekkers[13,14].

5.1. Acute Mountain Sickness (AMS)

This is very common in people who go to altitudes over about 3000 m and is characterized by headache, breathlessness, fatigue, insomnia, loss of appetite, nausea, dizziness and palpitations. Most of the symptoms begin a few hours after ascent and disappear after two or three days although the difficulties with sleeping often remain. No treatment is necessary although aspirin, acetaminophen (Tylenol) or ibuprofen (Advil) may be useful for the headache. Symptoms improve with rest and in occasional severe cases it may be necessary to descend. Acetazolamide (Diamox) reduces the incidence of acute mountain sickness by stimulating ventilation. The dose is 250 mg once or twice a day beginning on the morning of the ascent or the day before. A small dose of acetazolamide such as 125 mg taken at night often improves sleep. The drug has several side effects including increased urination, tingling of the fingers and toes, and making carbonated beverages taste flat. It should only be taken if needed and is a prescription drug.

5.2. High-Altitude Pulmonary Edema (HAPE)

This is a serious illness in which fluid moves out of the pulmonary capillaries into the air spaces of the lungs. The main symptom is increased shortness of breath and this frequently becomes worse at night. A physician can hear crackling sounds in the lung by using a stethoscope. The condition may progress to the point where the patient coughs up prink frothy fluid.

This is a medical emergency and necessitates removing the patient to lower altitude as soon as possible. Oxygen should be given if this is available but descent is imperative. Astronomers working at high altitude should adopt the "buddy" system so that someone is always available to help a sick person. Another wise precaution is to have two vehicles always available in case of mechanical difficulties.

5.3. High-Altitude Cerebral Edema (HACE)

This is a serious but fortunately rare condition where fluid leaks out of capillaries into the brain tissue. It often begins like acute mountain sickness but progresses to loss of balance, difficulties with walking, clouding of consciousness, irrational behavior and coma. The patient should be immediately removed to low altitude and given oxygen if this is available. The incidence of AMS, HAPE and HACE all increase as the altitude is raised.

6. Use of Supplementary Oxygen at High Altitude

As we have seen, all the medical effects of high altitude are caused by the low partial pressure of oxygen in the inspired air. It should therefore come as no surprise that the best way to counter the oxygen deprivation of high altitude is to add oxygen to the inspired air. There have been important technological advances in the last few years that have improved our ability to do this, the most significant being oxygen enrichment of rooms in which astronomers work.

It appears that among a small minority of astronomers there remains a prejudice against the use of supplementary oxygen. The common objections are that: 1) it is not necessary and "I can function perfectly well without it;" 2) it is technically too complicated and expensive to install; and 3) it is dangerous because of the fire hazard. None of these objections is valid. On the first, there is ample evidence that at altitudes of 5000 m and above, mental and physical performance are impaired. This is not so obvious at the lower altitude of 4200 m, and it is not easy to document for the reasons given earlier. However there is a wealth of evidence that people lose mental efficiency at that altitude, they make more errors, and they fatigue more rapidly. All these problems can be greatly helped by oxygen enrichment. The second objection that oxygen enrichment is technically difficult and expensive has been disproved by field trials over the last few years, one of the most convincing being that of the Caltech Cosmic Background Imager. Finally the fire hazard has been analyzed in great detail and simply does not exist if appropriate precautions are taken (see later). Here it should be emphasized that although the atmosphere is being oxygen-enriched, the resulting PO_2 is still much lower than the sea level value, and the fire hazard is much less than at sea level.

6.1. Oxygen Enrichment of Room Air

Oxygen enrichment of room air was suggested almost twenty years ago by Cudaback[3] in connection with telescope facilities on Mauna Kea but was never implemented. Since then there have been substantial technical advances. The subject been discussed at length elsewhere[15] and so only the main points will be covered here. The simplest way to introduce it is to describe a typical room used by astronomers from the California Institute of Technology for their Cosmic Background Imager at an altitude of 5050 m in north Chile.

The control room and laboratory each consist of a standard shipping container (7 ft × 7 ft × 40 ft) which are lined with insulation which is sufficient to maintain a 40ºC temperature difference with a 1 kW heater, and provided with lighting and electrical outlets. The living quarters are similarly outfitted, but of half the length. The room is entered through a double door that forms an airlock. Ventilation is by means of a pipe that extends from the door end to the far end of the room, and there is an exit port near the door. Fresh air is drawn into the ventilation duct by a variable electric fan. Oxygen is injected from the concentrators into a separate duct which extends the length of the room and has multiple outlets. The oxygen concentrators are located outside the room but in a protected compartment inside the container. The principle of the concentrators is that when air is pumped into a tube of synthetic zeolite at high pressure, nitrogen is preferentially adsorbed and the effluent gas has an oxygen concentration of 90-95%. After a short period the zeolite is unable to adsorb more nitrogen and the high pressure air is switched to a second tube while the first tube is purged of nitrogen using air at normal pressure. The only moving parts in the oxygen concentrator are a piston pump and the switching valve. A typical model is the AirSep New Life Elite (AirSep Corp., Buffalo, NY) which provides 5 $l.min^{-1}$ of 90-95% oxygen but similar devices are available from other manufacturers. These oxygen concentrators are used by the thousands in private homes to provide oxygen for patients with severe lung disease and are robust, self-contained, and require only 350 watts of electrical power. The cost of each unit is about $1,000. A typical room at the CBI with two occupants requires four of these units in parallel to raise the oxygen concentration of the room air from 21 to 27%. It is also possible to supply oxygen from liquid oxygen tanks but the running costs are about ten times higher in a typical facility[15].

The ventilation level of the room is maintained at the minimum acceptable level to reduce the amount of oxygen that has to be generated. We use the ASHRAE (American Society of Heating, Refrigerating, and Air Conditioning Engineers) 1975 standard which is 8.5 $m^3.h^{-1}$ per person. The carbon dioxide concentration in the room is monitored and kept at or below 0.3% (the concentration in air is about 0.03%). Substantially higher concentrations of CO_2 in the room can be present without causing a health hazard, or without the occupants being aware of them, but the CO_2 level is a useful index of the adequacy of ventilation. The oxygen concentration of the room is also monitored.

An oxygen concentration of 27% in the room was chosen to reduce the equivalent altitude to 3200 m. (The equivalent altitude is that which provides the same inspired P_{O_2} for a person who is breathing air.) Since the astronomers are living at San Pedro de Atacama (altitude 2440 m) and therefore will be acclimatized to this altitude, the increase in altitude to 3200 m is easily tolerated. It would be possible to raise the oxygen concentration of the room to about 32% without the fire hazard exceeding that of sea level air, but there is little point in doing this. The costs of oxygen enrichment in this facility are small. The four oxygen concentrators require only 1400 watts of power, a minor drain in the context of a sophisticated telescope facility. Sometimes the question comes up as to whether someone leaving an oxygen-enriched room and going into ambient air will feel dizzy, faint, or suffer in some other way. The answer is that people are completely unaware of either entering or leaving the oxygen-enriched environment (see later).

Additional information should be given about the possible fire hazard since this issue is frequently raised. The fire hazard in oxygen-enriched atmospheres has been analyzed in detail by the National Fire Protection Association[16]. They concluded that an atmosphere of increased burning rate for various materials including paper and fabrics is one that contains a percentage of oxygen greater than $23.5/P^{0.5}$, where P is the total pressure as a fraction of the sea level pressure. Based on extensive experimental studies it can be shown that an oxygen concentration of 27% at an altitude of 5050 m gives a burning rate that is approximately 70% of the sea level value[17]. The primary reason is that although oxygen has been added to the atmosphere, the P_{O_2} is still far below that of air at sea level. Note that the P_{N_2} also has an effect on burning rate because of its quenching action. Even so, common sense dictates that there should be no cigarette smoking or use of flammable gases and liquids in the oxygen-enriched room. Also volatile liquids require special handling because there is some evidence that they may ignite more easily at high altitude, and their vapors may spread more readily than at sea level. As long as these limitations are borne in mind they should not cause any great inconvenience.

Extensive studies on oxygen enrichment of room air have been carried out at the University of California White Mountain Research Station (altitude 3800 m). They have shown that some aspects of neurophysiological function will be improved at an altitude of 5000 m with 27% oxygen enrichment[18]. A series of studies have also been carried out on the effects of oxygen enrichment on sleep and all these have shown substantial benefits[19,20]. But probably the most convincing evidence of the value of oxygen enrichment at 5050 m comes from the experience of the astronomers in the CBI project. Their experience has been summarized as follows:

> The CBI was designed and constructed on the Caltech campus and tested there for a year before disassembly and shipping to Chile in August 1999. The same group was responsible for the reassembly on Chajnantor. For the first 10 days of telescope assembly we did not have oxygen and we tired quickly under even modest physical labor, and suffered from cold in the ~15 msec^{-1} and ~-5ºC conditions. Our fingers soon became numb, making construction work difficult. After an 8 hour shift at 5050 m we were completely exhausted and slept for ~12 hours. On day 11 we were for the first time able to use our portable oxygen units, and two senior group members began using supplemental oxygen and their efficiency improved remarkably. Physiologically the contrast with the preceding 10 days was striking - it was possible to work normally; heavy lifting and carrying

were much easier, and the problems with cold were much diminished. It was now possible to work without gloves for significant periods before fingers were too numb to continue, and fingers regained feeling much more rapidly than without the supplemental oxygen.

An interesting psychological factor was that, in spite of the extensive discussions of the use of oxygen the group had had and the planning for the use of oxygen prior to moving to Chile, once we were engaged in the construction in Chile there was significant resistance to the use of oxygen from group members who felt that they would do better to get acclimatized. A few days of working alongside those using oxygen quickly disabused them of this misconception. Astronomical projects planning to work at high altitude should be aware of the inherent resistance to the use of oxygen, and the "macho" view that it is not necessary. Unfortunately it is not easy when not on supplemental oxygen to assess one's own performance unless doing heavy physical work alongside someone who is using supplemental oxygen. Our experience led us to lay down strict rules regarding the use of oxygen on the project which were that no work should be done on the telescope, the power plant, in the machine shop or with power tools without the use of oxygen. Each member of the group has his or her own portable oxygen unit. We also always carry these units with us driving to and from the site in case of need while driving, which does happen occasionally.

After 3 weeks the site facilities were ready for use with enriched oxygen in the control building, the laboratory and two living quarters, and from that time on the difficulties of working at altitude were greatly reduced. Having oxygen-enriched sleeping quarters has proven important for observing with the CBI - in general we do not spend long periods at the site, but on occasion astronomers have spent 4-5 days continuously at the site with no ill effects. In addition our drivers generally sleep at the site while the astronomers are observing, and they get a good sleep in the oxygenated containers, thus ensuring that they are rested and alert for the drive back to San Pedro.

There were a number of physiological effects due to working at high altitude which were noticed by members of the CBI group. These depended on the amount of time which was spent at high altitude as well as on the wind chill. It would be hard to over emphasize just how much the use of oxygen helps in coping with both the wind an cold at high altitude. Conditions which become intolerable in ~15-20 minutes without supplemental oxygen can be tolerated for some hours with the use of supplemental oxygen. This has been experienced many times in the 4 years of operation of the CBI.

The most common physiological effects of high altitude are breathlessness, irritability, headaches, nausea and poor judgment. We quickly realized that heightened irritability was a factor and that in instances of disagreement the discussion should be deferred. In addition, lack of judgment was a significant factor. Although irritability was much reduced and judgment much improved in the oxygenated containers, we decided early on to take a cautious approach and defer discussion of controversial topics until we returned to our base in San Pedro; and we also learned to check the most critical decisions with staff in San Pedro or in Pasadena before proceeding.

Some people have voiced concerns that one might feel at a disadvantage if one moves directly from an oxygen-enriched room to the outside and also that acclimatization might be significantly slower if one uses supplemental oxygen. At the CBI we do this frequently, of course, and we have not experienced any adverse effects or symptoms.

A number of minor symptoms of working at altitude were also experienced by some members of the group. Some of these symptoms were related to dehydration. These symptoms included:

1) Loss of appetite. This depended strongly on the amount of time spent at high altitude.
2) Loss of body weight. This was related to (1) and was so severe in some cases that people with a usual body weight of 150 lb to 170 lb lost 15 lb to 20 lb of body weight.
3) Bright flashing arcs of light in the peripheral vision when blinking, possibly due to dehydration of the vitreous humor, which led to the retina being stretched. This was cured by drinking 6-8 glasses of water each day.
4) Fingernails separating from the skin further down the nail than usual and the tops of nails becoming very white. Finger ends tended to crack and split and take longer than usual to heal. This was only a problem for people spending a lot of time at high altitude and working in very cold conditions.
5) Constipation. This was a serious problem for some group members.

Table III shows the results of oxygen enrichment at various sites of interest to astronomers. At the lowest site, the Barcroft Facility of the White Mountain Research Station where much of the early work on oxygen enrichment was carried out, the altitude is only 3800 m and the oxygen concentration in the room is 24%. This gives an equivalent altitude of 2800 m and an alveolar P_{O_2} of about 68 torr. The table shows how the oxygen concentration is increased for higher altitudes. For example, at Chajnantor (altitude 5050 m) the oxygen concentration used by the Cosmic Background Imager group is 27% giving an equivalent altitude of about 3200 m. At the highest altitude of 5800 m, the oxygen concentration is 30% also giving an equivalent altitude of 3200 m. The values for alveolar P_{O_2} with oxygen enrichment are also shown on Figure 1.

The maximum safe oxygen concentrations at the four altitudes are also shown in Table III. Note that in every case it would be possible to safely increase the oxygen concentration and thus reduce the equivalent altitude. However there is little to be gained by reducing the equivalent altitudes any further because these are easily tolerated. The chosen values represent a good compromise between a comfortable altitude, the cost of providing oxygen, and the possible fire hazard.

It is important to recognize that each situation of high altitude astronomical observations is unique, and therefore the use of oxygen must be adapted to the particular needs and applications of the project. In general, it would be better if astronomers did not have to work at the telescope site, and if a small staff could carry out the vital operations which require physical presence at the site. In such situations, the staff would benefit from the same type of facilities as have been set up for the CBI, and supplemental oxygen should certainly be made available.

6.2. Portable Oxygen

Of course oxygen enrichment of room air as described above can only be used in closed spaces. Frequently staff have to work on equipment outside closed spaces and portable oxygen can be valuable here. A small portable oxygen cylinder is used and the oxygen is delivered via cannulas that are placed just inside the nostrils. Admittedly this is more cumbersome than oxygen enrichment of room air where the astronomer is not aware of the fact that he or she is using supplemental oxygen. The experience at the CBI has been that while portable oxygen is not as convenient, it is essential, and the awkwardness of carrying an oxygen cylinder is well worth it. In constricted spaces, the cylinder and controller can generally be placed close enough to the work area to allow the continued use of oxygen, thus greatly increasing both comfort and efficiency. However portable oxygen is used by thousands of patients with severe lung disease and is certainly feasible. The equipment includes an economizer that senses the pressure in the cannulas so that when this falls slightly at the beginning of inspiration, a pulse of oxygen is delivered. Again the experience of the astronomers at the CBI is that portable oxygen greatly improves their efficiency.

7.0 Conclusion

There are good scientific reasons to site telescopes at altitudes of 5000 m and above, but these altitudes can seriously impair human mental and physical performance and quality of sleep. However the introduction of oxygen concentrators which allow oxygen enrichment of the air in the rooms where the astronomers work or sleep makes high-altitude astronomy feasible. The technique is not expensive, and because it increases the efficiency of the astronomers, the benefit in relation to cost is substantial. As indicated above, the only running cost of oxygenating a module at the CBI is that of providing 1400 watts of electrical power. Moving from an oxygen-enriched environment to ambient air at high altitude causes no serious problems. A common misconception within the astronomy community is that acclimatization to high altitude removes the deleterious effects of oxygen deprivation, but this is a fallacy. Oxygen enrichment of room air has been used by the California Institute of Technology Cosmic Background Imager at an altitude of 5050 m for four years with considerable success. The technique could also be used at more modest altitudes such as that of Mauna Kea (4200 m) with consequent improvements in human mental and physical performance.

Acknowledgements

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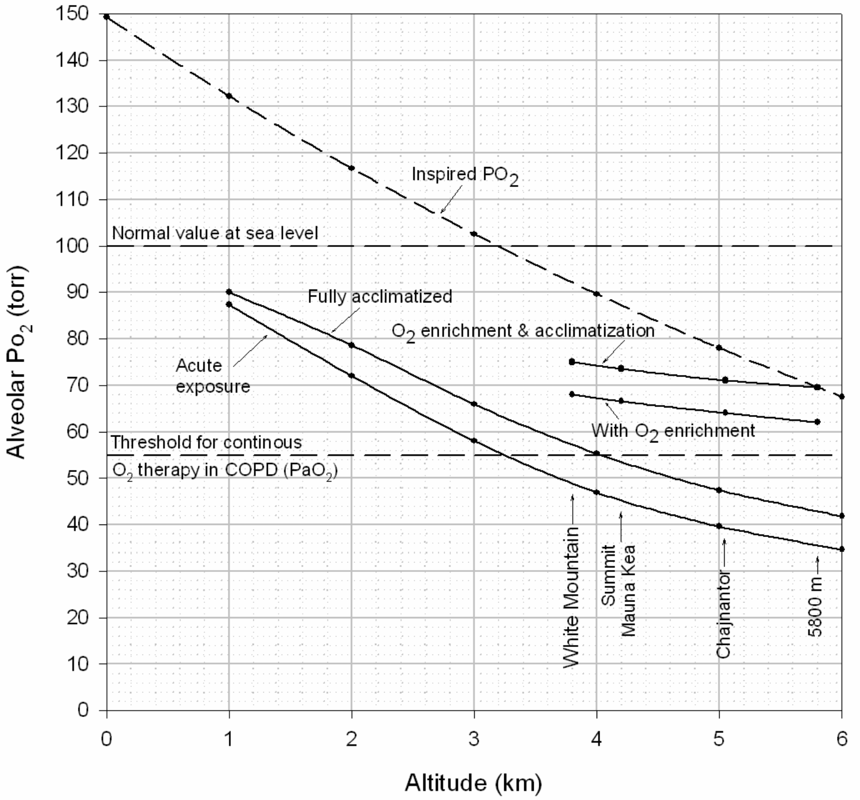
Figure Caption

Figure 1 Alveolar P_{O_2} values for people at high altitude who are acutely exposed (no acclimatization) or fully acclimatized. The data for these two lines come from Rahn and Otis[11]. Note that all the values are far below the normal sea level value of 100 torr. The lower broken line at a P_{O_2} of 55 torr indicates the value below which patients with severe lung disease at sea level are entitled to continuous oxygen therapy under Medicare or the N.H.S. (This is actually the arterial P_{O_2} which in normal subjects is 2-3 torr below the alveolar value and the diagram shows the best case.) Note that an astronomer on the summit of Mauna Kea who is completely acclimatized, a process that takes about 10 days, will nevertheless have a P_{O_2} below the value which entitles him or her to continuous oxygen therapy at sea level if he has lung disease. Typical alveolar P_{O_2} values for oxygen enrichment are also shown according to the oxygen concentrations shown in Table III. The inspired P_{O_2} is shown by the uppermost broken line. COPD, chronic obstructive pulmonary disease; Pa_{O_2}, partial pressure of O_2 in arterial blood.



Alveolar Po$_2$ (torr)
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
Altitude (km)
0
1
2
3
4
5
6
Inspired PO$_2$
Normal value at sea level
Fully acclimatized
O$_2$ enrichment & acclimatization
Acute exposure
With O$_2$ enrichment
Threshold for continous O$_2$ therapy in COPD (PaO$_2$)
White Mountain
Summit Mauna Kea
Chajnantor
5800 m

Figure 1

Table I Inspired partial pressure of oxygen (P_{O_2}) at various altitudes

Site	Altitude m	Barometric Pressure torr	Inspired P_{O_2} torr	Inspired P_{O_2} % of S.L.
Sea Level	0	760	149.2	100
White Mountain	3800	487	92.1	61.7
Mauna Kea	4200	464	87.3	58.5
Chajnantor	5050	417	77.4	51.9
Nearby Peak	5800	379	69.5	46.6

S.L. sea level

Table II Mental ability expressed as a fraction of ability at sea level for unacclimatized individuals (from [21])

Altitude (m)	Visual Sensitivity	Attention Span	Short Term Memory	Arithmetic Ability	Decision Making Ability
2500	83%	100%	97%	100%	100%
3500	67%	83%	91%	95%	98%
4200	56%	70%	83%	92%	95%
5000	48%	57%	76%	86%	90%

Table III Effects of oxygen enrichment at various high altitude sites

Site	Altitude m	O_2 Concentration %	Equivalent Altitude m	Alveolar PO_2 torr	Maximum Safe O_2 Concentration %
White Mountain	3800	24	2800	68	29.3
Mauna Kea	4200	25	2900	67	30.0
Chajnantor	5050	27	3200	64	31.7
Adjacent Peak	5800	30	3200	64	33.2