HIGH LIFE

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A History of High-Altitude Physiology
and Medicine

John B. West

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*To Sir Edmund Hillary who, with Griffith Pugh,
introduced me to high-altitude physiology
through the Silver Hut expedition in 1960.*

PREFACE

THE history of high-altitude physiology and medicine is such a rich and colorful topic that it is perhaps surprising that no one has undertaken a comprehensive account before. There are so many interesting ramifications, from the early balloonists to the various high-altitude expeditions, culminating in the great saga of climbing Mt. Everest without supplementary oxygen. Underpinning this variety is the basic biological challenge of hypoxia and the ways organisms adapt to it, a subject that is of key importance in medicine and many other life sciences, encountered as it is by organisms throughout the animal kingdom.

I hope that this book will be of interest to a wide range of people, from biologists and physiologists to pulmonologists and others who manage patients with hypoxemia. The topic should also appeal to those who love the mountains including trekkers, skiers, climbers, and mountaineers.

The book begins with a short introductory chapter to set the scene for the non-scientist. It then follows a general chronological sequence beginning with the Greeks and ending with contemporary events. In some places, however some compromises have been made to group together areas of related interest. For example, in Chapter 4 the controversy about oxygen secretion is traced from the 1870s to the 1930s and includes the Anglo-American Pikes Peak Expedition of 1911 and the International High-Altitude Expedition to Cerro de Pasco, Peru during 1921–1922. It makes sense to consider these events together. Another example is in Chapter 7, which is devoted to permanent residents of high altitude. It is convenient to follow this topic from the early views of the Incas through the 1935 International High-Altitude Expedition to Chile, to modern studies of Tibetans.

Although this book covers a very wide area, it does not examine all aspects of high-altitude physiology and medicine. For example, if somebody wants information on the modern history of chemoreception or endocrine function at high altitude, these are not dealt with separately. Topics like these are best approached in conjunction with other books on high-altitude physiology and

medicine, for example Ward *et al.* (1995). By the same token, although Chapter 8 deals with some aspects of aviation medicine, this subject is not treated exhaustively and other books such as DeHart (1996) should be consulted.

Finally, as indicated at the beginning of Chapter 12, my goal has been to follow the history of high-altitude physiology and medicine up to the present day. This involves risks because so many people are now working in the field, and almost certainly there are important omissions. Yet, it would be a great loss not to mention some of the interesting new developments such as the Pyramid Laboratory near the Everest Base Camp and the extraordinary problems posed by modern mining operations in Chile, where workers commute from sea level to altitudes up to 4600 m. I welcome constructive suggestions, particularly the identification of factual errors.

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La Jolla, California
October 1997

J.B.W.

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INTRODUCTION

AS this is being written, news is coming through that at least seven people died in May 1997 while attempting to climb Mt. Everest. Last year¹ during the same month the number of fatalities on the mountain was 12. Why is high altitude such a physiological and medical challenge? This brief introduction sets the scene for the non-scientist.

People go to high altitude for many reasons. First, large numbers now go for recreational purposes including skiing, trekking, and mountaineering. Most of these people reside near sea level and many will have a few symptoms of acute mountain sickness shortly after they arrive, including headache, fatigue, light-headedness, loss of appetite, nausea, and insomnia. However, their tolerance to high altitude normally improves over a few days or weeks by the process of acclimatization. A few people will develop high-altitude illnesses (see Chapter 5) but most will thrive in the invigorating environment. Mountaineers who climb to extreme altitudes will have special problems (see below, and Chapters 6 and 9).

Second, nearly 140 million people live at altitudes above 2500 m or 8000 ft (WHO, 1996). Many live much higher. For example, it is estimated that over 50,000 people in Peru reside above 4000 m (13,100 ft), and caretakers of a mine in Chile have lived at nearly 6000 m (nearly 20,000 ft). Permanent residents of high altitude, some of whom have been there for many generations, probably benefit from evolutionary adaptation, and most never consider living anywhere else (see Chapter 7).

There is a third group which is much smaller but growing rapidly, that consists of people who commute to high altitude for commercial or scientific reasons. Typical examples include workers in mines at altitudes up to 4600 m in the South American Andes, especially Chile, and astronomers in observatories planned for altitudes as high as 5000 m. The commuting patterns that have recently developed are remarkable. In a typical high-altitude mine in Chile, for example, the workers are bused up to an altitude of 4500–4600 m where they spend 7 days working, and are then bused down to sea level to

spend the next 7 days with their families. This cycle is repeated indefinitely. In the case of planned telescopes at 5000 m, the workers will live at about 2400 m and commute daily to the telescope site (see Chapter 12). These new commuting patterns raise several physiological and medical problems which are poorly understood.

The reason why high altitude poses enormous physiological and medical challenges is that the amount of oxygen in the air is reduced. As we go higher, the barometric pressure falls, just as when we are submersed in water, the pressure rises. Indeed, Torricelli (see Fig. 1.11), who invented the mercury barometer in the mid-seventeenth century stated, "We live submerged at the bottom of an ocean of the element air, which by unquestioned experiments is known to have weight."

The higher we go, the lower the pressure falls. At an altitude of about 5800 m (about 19,000 ft) the pressure falls to half the normal sea level value of 760 mm Hg. At the summit of Mt. Everest, which can just be reached by elite climbers without supplementary oxygen, the pressure is about one-third of the sea level value. Since the oxygen concentration of the air does not alter with altitude (at least up to altitudes of interest to us), the pressure of oxygen in the air (technically the "partial pressure") falls proportionally with the barometric pressure. This "hypoxia," as it is called, is responsible for most of the physiological changes and potential medical problems that occur at high altitude. Cold, especially wind chill, can also be a serious hazard for mountaineers.

Everyone who goes from near sea level to high altitude for more than a day or so is greatly helped by the process of acclimatization (see Chapter 4). This powerful mechanism is critical to survival at very high altitudes and is a classical example of how the human body can adapt to a hostile condition. A simple example shows how effective this process can be. Suppose a normal subject is acutely exposed to the barometric pressure which exists on the summit of Mt. Everest by going into a low-pressure chamber such as is used to train pilots. He or she will immediately become mentally confused, and consciousness will probably be lost within 2 or 3 minutes. With the advantages of acclimatization, however, many climbers have now reached the summit of Mt. Everest without supplementary oxygen, though this still remains an enormous challenge.

The most important feature of acclimatization to high altitude is an increase in the rate and depth of breathing. This increase in "ventilation," as it is called, is brought about by stimulation of chemoreceptors by the low oxygen pressure in the arterial blood. A chemoreceptor is a specialized tissue that responds to its chemical environment by sending nerve impulses to the brain. As a result, someone who acclimatizes to an altitude of 5000 m will almost double his or her ventilation. In order for a climber to reach the summit of Mt. Everest, he must increase his ventilation some fivefold (see Chapter 11). Anecdotal evidence of the breathlessness of climbers on the summit comes from tape recordings that have been made there. The climbers are so short of breath that

they need to pant after every two or three words! The reason why the increase in ventilation is so critically important is that it raises the pressure of oxygen in the alveoli in the depths of the lung to viable levels. This is where the exchange of oxygen and carbon dioxide between air and blood takes place. At the same time, the increase in ventilation greatly reduces the pressure of carbon dioxide.

The extent to which people increase their breathing when they go to high altitude (i.e., their ventilatory response to hypoxia) depends on their genetic makeup. Some people increase their breathing much more than others. Climbers who have a low ventilatory response to hypoxia tend to tolerate very high altitudes badly. The test can be carried out at sea level by giving somebody a low oxygen mixture to breathe.

Interestingly, many people who are born at high altitude have a relatively low ventilatory response to hypoxia. This seems to be paradoxical, although it may have the advantage that it protects these people from uneven breathing during sleep (see below). It is probable that these permanent residents of high altitude have other adaptations at the tissue level that we do not yet understand.

Another well-known feature of acclimatization is an increase in the number of red cells in the blood. These cells are responsible for carrying the oxygen. As an example, a permanent resident in the Peruvian Andes at an altitude of 4600 m typically has his red cell concentration increased by about 30%. This "polycythemia," as it is called, enhances the ability of the blood to carry oxygen. However, the value of polycythemia in the acclimatization process is not as clear as it was once thought to be. Severe polycythemia makes the blood very thick and difficult to move through the capillaries in muscles, brain, and other tissues. As a result, it may lead to problems with unloading of oxygen to the peripheral tissues. Indeed, it has been shown that some permanent residents of the high Andes can actually do more physical work when the concentration of red cells in their blood is reduced by bloodletting.

Other features of acclimatization include an increase in the concentration of capillaries in peripheral tissues and increases in the enzymes that facilitate the utilization of oxygen within cells. However, it is likely that some of the acclimatization processes at the cellular level have yet to be discovered.

Many features of the evolutionary adaptation of permanent residents to high altitude are similar to those of the process of acclimatization which occur when lowlanders go to high altitude. Recent studies suggest that Tibetans may have progressed farther in the evolutionary adaptation process than residents of the Andes. This is consistent with the fact that people have probably inhabited the Tibetan plateau for a much longer period of time than Andeans have been at high altitude. Features that suggest better adaptation include less polycythemia, greater ventilation, and a lower incidence of chronic mountain sickness. However these are recent findings and some are controversial (see Chapter 7).

One of the great sagas of this century has been the ascent of Mt. Everest without supplementary oxygen, and many mountaineers continue to regard this as the ultimate challenge. The story is dealt with in Chapters 6 and 9. In the first decade of the century, the Duke of the Abruzzi reached an altitude of 7500 m in the Karakoram mountains despite the fact that, towards the end of the last century, there were gloomy predictions that mountaineers could never ascend above about 6500 m. An important expedition to Pikes Peak in 1911 (described in Chapter 4) concluded that, at high altitude, the lungs actively secrete oxygen into the blood. This was later disproved but the great British physiologist J. S. Haldane believed in oxygen secretion until his death in 1936. In 1919, the mountaineer-physiologist Alexander Kellas predicted that Everest could be climbed without supplementary oxygen if the technical difficulties were not too great. Indeed, in 1924 E. F. Norton climbed to within 300 m of the summit without supplementary oxygen, a record that was not surpassed for some 50 years. Yet in the 1930s several studies by eminent physiologists suggested that the summit could never be reached without supplementary oxygen. It was not until 1978, 54 years after Norton, that the last 300 meters were conquered by Messner and Habeler.

In the 1980s, two major studies were made of the physiological challenges posed by climbing Everest without supplementary oxygen. An analysis of the critical factors on the summit showed that these were the barometric pressure, the extent of the increase in ventilation, and the maximal amount of oxygen that the body could consume. The first measurements of these were obtained by the American Medical Research Expedition to Everest in 1981, and in 1985 a simulated climb in a low-pressure chamber, Operation Everest II, greatly clarified the physiological adaptations at extreme altitudes. Both of these studies are described in Chapter 11.

Various forms of altitude sickness are recognized (see Chapter 5). New-comers to high altitude frequently complain of headache, fatigue, dizziness, palpitations, lack of appetite, nausea, and insomnia. This constellation is known as acute mountain sickness and usually resolves after 2 or 3 days at medium altitudes. Prior administration of the drug acetazolamide (Diamox) reduces the incidence of acute mountain sickness.

A more severe illness is high-altitude pulmonary edema in which the capillaries in the lung are damaged by high pressure and leak fluid from the blood into the alveolar spaces (see Chapters 5 and 12). The best treatment for this potentially fatal condition is to take the patient to lower altitude as quickly as possible. Another serious though less common problem is high-altitude cerebral edema where fluid leaks from the blood into the brain tissues. Again, descent is by far the best treatment. Long-term residents at high altitude sometimes develop an ill-defined syndrome characterized by fatigue, reduced ability to exercise, very low levels of oxygen in the blood, and marked polycythemia. This is called chronic mountain sickness (see Chapter 7).

Newcomers to high altitude often complain that the most distressing period is during the night when they try to sleep. Periodic breathing frequently occurs. This is characterized by gradual waxing and then waning of breathing movements, and there is often a period of no breathing at all (apnea) which may last for 10 seconds or more (see Chapter 3). Acetazolamide reduces the incidence and severity of periodic breathing. Permanent residents of high altitude develop less periodic breathing apparently because of their reduced ventilatory response to hypoxia as indicated earlier. This is the case for the Sherpas who live in the Everest region. Periodic breathing results in very low levels of oxygen in the blood, so the avoidance of periodic breathing may explain the evolutionary advantage of the reduced ventilatory response to hypoxia which initially seems paradoxical.

New challenges continue to develop at high altitude (see Chapter 12). Some of the most demanding were alluded to earlier in the context of mine workers who commute from near sea level to altitudes of 4500 m and above. One new development is the addition of oxygen to the air conditioning of some parts of the mine. Possible areas include dormitories, offices, conference rooms, laboratories, and even the cabins of large trucks and mechanical shovels. Every 1% of oxygen enrichment (e.g., increasing the oxygen concentration from 21 to 22%) is equivalent to reducing the altitude by 300 m. In other words, 5% oxygen enrichment in a mine at 4500 m reduces the equivalent altitude to 3000 m, which is much more easily tolerated. Oxygen enrichment has become feasible because large amounts of oxygen can now easily be produced by oxygen concentrators, and also liquid oxygen is relatively inexpensive. This is just one example of how the physiological and medical problems of high altitude continue to evolve.