Chapter 22

PHYSICAL PERFORMANCE AT VARYING TERRESTRIAL ALTITUDES

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INTRODUCTION

The study of physical performance has long been of interest to the military. Scientific studies of military members performing a variety of tasks were among the earliest nonclinical investigations in the area of applied physiological research.[1,2] For example, numerous reports have described the energy cost of marching at various speeds with and without loads under controlled conditions.[1,3–8] It is well accepted that external stresses such as increased load carriage and rugged terrain features can lead to decreases in functional capacities. Yet, despite the considerable mechanization of the modern military, service members still have the burdensome task of carrying essential, often heavy equipment. In mountainous regions, the load carried will almost certainly increase—owing to the additional weight of protective clothing and technical equipment. Other factors that have profound negative influence on military operations in the mountains include steep, rugged, and constantly changing terrain; unpredictable weather conditions; snow-covered ground; and mountain sickness.[9,10] Military physical performance in the mountains may also be adversely affected by sleep deprivation; increased physical or emotional stress, or both; caloric and fluid restrictions; reduced visibility; equipment failures; inadequate communications; and lack of specialized medical equipment.[11]

The hypoxia (ie, low inspired oxygen pressure) associated with mountain (ie, actual) or altitude (ie, experimental) exposures reduces sustained physical performance capabilities to a degree directly proportional to the elevation, with the magnitude of the reduction associated with initial exposure usually greater than that associated with continued exposure. Because of hypoxia-induced physical performance decrements, military personnel rapidly transported from low to high terrestrial elevations should not be committed immediately to patrolling operations, entrenchment, combat, or other physically demanding duties, nor should they be expected to perform as well as they did at sea level.[9] Although it is generally accepted that more-frequent rest breaks, increased time for task completion, and a reduction in the number of daily tasks will be required for proper recovery and should be included in operational planning, the combination of all the above factors makes it difficult or impossible to precisely predict the extent of the negative impact on unit effectiveness that an operation will encounter, or to provide exact guidelines to improve mission success. Mountaineering training (provided by sites such as the Northern Warfare Training Center at Fort Greely, Alaska; the Marine Mountain Warfare Training Center, Bridgeport, California; and the Mountain Warfare Training Site, Jericho, Vermont) is essential to fully appreciate the complexity of the problems to be encountered in mountain environments.

Initially, interest in the human capacity to do physical work at altitude was primarily stimulated by early mountaineering experiences.[12,13] Although mountain climbing is strenuous and can require high levels of skill, the focus of a noncompetitive climb is often related more to successfully completing mountaineering tasks and enjoying the scenery than in climbing the greatest distance in the shortest time. Conversely, military service members are deployed to mountain areas on the basis of their units' mission, and not for recreation or personal challenge. Tactical operations dictate the timing, duration, and location of the mission, often exposing service members to terrain and environmental conditions that would usually not be considered recreational.[11]

Occupational requirements for military operations, mining, aviation, and space science stimulated research that focused on functional limitations, adjustments, and processes of acclimatization at altitudes greater than 3,000 m during rest and low-to-moderate intensity activities.[14,15] Even though in the first half of the 20th century one third of the world's population lived above an altitude of 2,000 m,[16] few early physiological investigations had been conducted in the low-to-moderate altitude range between 2,000 and 3,000 m. [Other experts in epidemiology use a different estimate—a number considerably lower but still enormous—of the world's population living at high altitude: for example, by the 1990s nearly 140 million people resided above 2,500 m (8,000 ft).[17,18]—RFB, ed.] Not until reports of subnormal athletic performances in the longer-lasting events in the 1955 Pan American Games and the 1962 World Pentathlon World Championships in Mexico City (2,300 m), and the 1959 National Amateur Athletic Union at Boulder, Colorado (1,630 m),[19–21] did scientific investigations include the effects of hypoxic stress of more moderate altitudes.

The choice of Mexico City in 1963 as the site for the 19th Olympiad in 1968 stimulated much research on the effects of altitude.[22] International symposia in Switzerland (1965), the United States (1966) and Italy (1967) summarized findings from research and competitive athletic sources and made recommendations to the International Olympic Committee for the 1968 Olympics. Many,[19,23–26] although not all,[27–30] reports from this period indicated that acute altitude exposure impaired exercise performance, while residing or training (or both) at altitude greatly improved altitude maximal or submaximal exercise performances. At this time, it also became apparent that during altitude training and competition, the exercise performance of some but not all athletes was adversely affected, for reasons not well understood.[24,26] Not surprisingly, coaches and representatives of sea-level countries were concerned that

- residence and exercise training at altitude would confer an unfair advantage over those who resided and trained at sea level;
- it was not appropriate to conduct the Olympic trials at lower altitudes to choose individuals for competitions at higher elevations; and
- the moderate elevation of Mexico City would be deleterious to the health of elite athletes coming from sea level.

Although previous competitions at moderate altitudes had provided a general knowledge of what was to be expected from a low-altitude athlete competing at a higher altitude, much of the available information was incomplete or contradictory. For example, recommendations made to the International Olympic Committee for the length of time an endurance athlete should train at altitude prior to competition ranged from less than 48 hours[16] to a minimum of 4 to 6 weeks.[31] Resolution of many of these issues was seen as having important implications for potential military deployment and conflict at altitude.[5]

Since the 1968 Olympics, interest in the effects of altitude residence and exercise training on physical performance at altitude or sea level for civilians and military has not waned.[32] Intensive study by many research, sport, and military organizations has provided some answers to questions regarding the effects of altitude exposure on physical performance. While there appears to be a consensus in the scientific literature that endurance exercise training at altitude improves exercise performance at altitude,[33] controversy still exists whether endurance training or residence at altitude improves subsequent endurance performance.[34–37]

PHYSICAL PERFORMANCE

The Effects of Altitude on Maximal Aerobic Power

The ability to perform sustained aerobic muscular exercise is assessed using the maximal rate of oxygen uptake ($\dot{V}O_2max$). This widely used performance index is reproducible[38,39] and generally accepted as the single best measure of the functional limit of the respiratory and circulatory systems to deliver oxygen to active muscles and the ability of the active muscles to utilize the oxygen delivered.[40] Maximal aerobic power can be affected by factors that alter any of the processes involved in oxygen transport or utilization. At altitude, a person is exposed to a progressive decrease in atmospheric pressure, with resultant declines in inspired, alveolar, and arterial oxygen pressures. As a consequence of the progressive hypoxia associated with increasing altitude, $\dot{V}O_2max$ declines at a rate inversely proportional to the elevation.[41]

Figure 22-1 illustrates the relationship of the measured percentage of decline in $\dot{V}O_2max$ with increasing actual or simulated elevations (ie, hypobaric chambers or breathing hypoxic gas). The wide range of the mean percentage of decline in $\dot{V}O_2max$ at nearly all altitudes reflects variability owing to differences in experimental design and procedures and physiological differences among subjects (Exhibit 22-1).

The relative contributions of these sources of variation to $\dot{V}O_2max$ decrement differences at a given altitude have yet to be quantified. It is important to note that even under ideal experimental conditions at sea level, owing to measurement error and individual biological variation, 68% of the time values of $\dot{V}O_2max$ for repeat tests can vary by as much as ± 5.6%; and 98% of the time can vary by as much as ± 11.2%.[39]

The mean data points in Figure 22-1 represent a database derived from literature sources. The regression line generated from these data provides a visual reference. Systematically isolating and grouping an adequate number of studies with similar experimental designs or subject characteristics from within this database, and then comparing the relative positions of the subgroupings to the entire database, allows a qualitative assessment of the relative importance of various factors in accounting for the total variation.

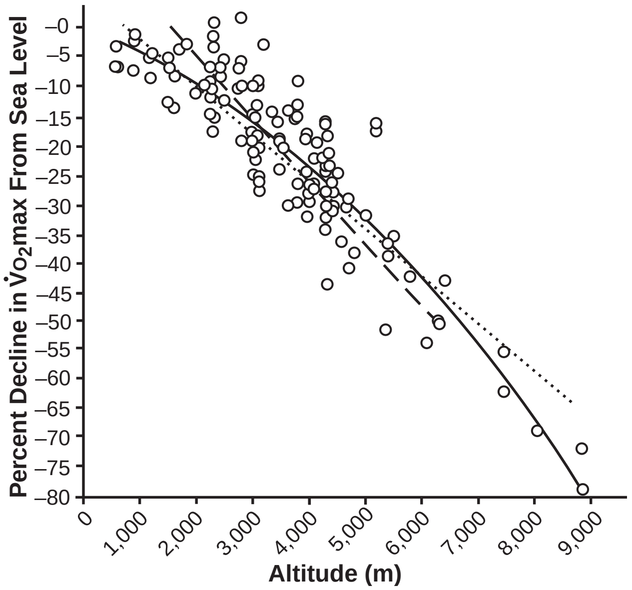

Fig. 22-1. Maximum oxygen consumption ($\dot{V}O_2$max) decreases with increasing elevation. Each of the 146 points (unfilled circles) on the graph represents a mean value derived from 65 different civilian and military investigations* conducted at altitudes from 580 m[1] to 8,848 m.[2,3] Multiple mean data points for a study were included if the study entailed more than one of the following: (1) elevation, (2) group of test subjects, or (3) exposure duration. For studies using hypoxic gas mixtures, inspired oxygen values were converted to altitude equivalents. Mean values are reported because they were the only values common to all investigations. A database regression line (thick curvilinear line) was drawn using the 146 points. Because each of these data points is a mean value of many intrainvestigation individual determinations of $\dot{V}O_2$max, the regression line represents possibly thousands of $\dot{V}O_2$max test values and therefore provides a truer approximation for the expected average decrement at each elevation. Also included are the regression lines of Buskirk and colleagues[4] (dashed line) and Grover and colleagues[5] (dotted line), which represent two of the most-often-quoted relationships of the decrement in $\dot{V}O_2$max to an increase in elevation. Reproduced with permission from Fulco CS, Rock PB, Cymerman A. Maximal and submaximal exercise performance at altitude. *Aviat Space Environ Med.* 1998;67(8):794.

Sources for the figure legend: (1) Gore CJ, Hahn AG, Scroop GS, et al. Increased arterial desaturation in trained cyclists during maximal exercise at 580 m altitude. *J Appl Physiol.* 1996;80:2204–2210. (2) Cymerman A, Reeves JT, Sutton JR, et al. Operation Everest II: Maximal oxygen uptake at extreme altitude. *J Appl Physiol.* 1989;66(5):2446–2453. (3) West JB, Boyer SJ, Graber DJ, et al. Maximal exercise at extreme altitudes on Mount Everest. *J Appl Physiol.* 1983;55:688–698. (4) Buskirk ER, Kollias J, Picon-Reategui E, Akers R, Prokop E, Baker P. Physiology and performance of track athletes at various altitudes in the United States and Peru. In: Goddard RF, ed. *The Effects of Altitude on Physical Performance.* Albuquerque, NM: The Athletic Institute; 1967: 65–72. (5) Grover RF, Weil JV, Reeves JT. Cardiovascular adaptation to exercise at high altitude. In: Pandolf KB, ed. *Exercise and Sport Science Reviews.* 14th ed. New York, NY: Macmillian; 1986: 269–302.

*Sources for the data points are contained in the Attachment at the end of this chapter.

Minimal Altitude for Decrement of, and the Rate of Decline in, Maximal Aerobic Power

Figure 22-1 shows the minimal altitude at which a decrease in $\dot{V}O_2$max has been detected and the rate at which it declines with increasing elevation. Three regression lines have been drawn: one representing data of the current database and the other two representing the more commonly cited relationships in the scientific literature.[42,43] The largest differences between the three lines occur at the lowest and the highest altitudes but the data points at all three lines are at similar locations at the intermediate altitudes. Buskirk and colleagues[42] suggested that there is minimal decrement in $\dot{V}O_2$max until approximately 1,524 m, with an average linear decline of 3.2% for every additional 305 m of altitude (dashed line). When this relationship was first proposed in 1966, the altitude at which $\dot{V}O_2$max began to decline and whether the $\dot{V}O_2$max decline remained linear at the higher altitudes were not apparent, because there was a paucity of data at altitudes less than 2,500 m and greater than 6,000 m. In more recent years, $\dot{V}O_2$max has been determined in subjects of varying fitness levels at lower[44–59] and higher[60,61] altitudes. Using information from some of these studies,[57,61] Grover, Weil, and Reeves[43] suggested in 1986 that the decline in $\dot{V}O_2$max begins at about 700 m, with a linear reduction of 8% for every additional 1,000 m of altitude up to approximately 6,300 m. In support of their contention, Jackson and Sharkey[34] reported in 1988 that athletes who reside at sea level and train at the Olympic Training Center in Colorado Springs, Colorado (altitude 1,881 m), exhibit a loss in $\dot{V}O_2$max of approximately 1% for every 305 m of ascent above sea level (this line is not shown in Figure 22-1). Consistent with these reports,[34,43] Gore and colleagues[62] reported in 1996 that at 580 m, $\dot{V}O_2$max declines 3.6% in fit, untrained individuals (statistically not significant) and 7% in elite ath-

EXHIBIT 22-1

POTENTIAL SOURCES OF VARIATION OF THE MEAN PERCENTAGE OF DECLINE IN $\dot{V}O_2$MAX IN COMPETITION AT ALTITUDE

- Subjects' fitness levels
- Residence at altitude prior to a study
- Subjects' gender
- Changes in conditioning level resulting from increased activity during the exposure
- Subjects' smoking status
- Subjects' motivation
- Subjects' age
- Hypoxic ventilatory response
- Altitude sickness (acute mountain sickness, high-altitude pulmonary edema, and high-altitude cerebral edema)
- Sample size
- Rate of ascent to altitude
- Duration of exposure (eg, acute vs chronic)
- Timing of $\dot{V}O_2$max measurements (eg, preacclimitazation and postacclimatization)
- Differences between training and exercise testing modes
- Use of inappropriate exercise mode (eg, elite runners tested with bicycle ergometers)
- Altitude-induced muscle wasting

Sources: (1) Dill DB, Adams WC. Maximal oxygen uptake at sea level and at 3,090-m altitude in high school champion runners. *J Appl Physiol.* 1971;30:854–859. (2) Faulkner JA, Kollias J, Favour CB, Buskirk ER, Balke B. Maximum aerobic capacity and running performance at altitude. *J Appl Physiol.* 1968;24:685–691. (3) Hansen JE, Vogel JA, Stelter GP, Consolazio CF. Oxygen uptake in man during exhaustive work at sea level and high altitude. *J Appl Physiol.* 1967;23:511–522. (4) Jackson CG, Sharkey BJ. Altitude, training and human performance. *Sports Med.* 1988;6:279–284. (5) Kollias J, Buskirk ER. Exercise and altitude. In: Johnson WR; Buskirk ER, eds. *Science and Medicine of Exercise and Sport.* 2nd ed. New York: Harper and Row; 1974: 211–227. (6) Howley ET, Bassett DR Jr, Welch HG. Criteria for maximal oxygen uptake: Review and commentary. *Med Sci Sports Exerc.* 1995;27:1292–1301. (7) Berglund B. High-altitude training: Aspects of haematological adaptation. *Sports Med.* 1992;14:289–303. (8) Boutellier U, Marconi C, Di Prampero PE, Cerretelli P. Effects of chronic hypoxia on maximal performance. *Bull Europ Physiopath Resp.* 1982;18:39–44. (9) Buskirk ER, Kollias J, Picon-Reategui E, Akers R, Prokop E, Baker P. Physiology and performance of track athletes at various altitudes in the United States and Peru. In: Goddard RF, ed. *The Effects of Altitude on Physical Performance.* Albuquerque, NM: The Athletic Institute; 1967: 65–72. (10) Dill DB, Hillyard SD, Miller J. Vital capacity, exercise performance, and blood gases at altitude as related to age. *J Appl Physiol.* 1980;48:6–9. (11) Dill DB, Robinson S, Balke B, Newton JL. Work tolerance: Age and altitude. *J Appl Physiol.* 1964;19:483–488. (12) Lawler J, Powers SK, Thompson D. Linear relationship between $\dot{V}O_2$max and $\dot{V}O_2$max decrement during exposure to acute altitude. *J Appl Physiol.* 1988;64:1486–1492. (13) Schoene RB, Lahiri S, Hackett PH, et al. Relationship of hypoxic ventilatory response to exercise performance on Mount Everest. *J Appl Physiol.* 1984;56:1478–1483. (14) Shephard RJ, Bouhlel E, Vandewalle H, Monod H. Peak oxygen uptake and hypoxia. *Int J Sports Med.* 1988;9:279–283. (15) Terrados N, Melichna J, Sylven C, Jansson E, Kaijser L. Effects of training at simulated altitude on performance and muscle metabolic capacity in competitive road cyclists. *Eur J Appl Physiol Med.* 1988;57:203–209. (16) Young AJ, Cymerman A, Burse RL. The influence of cardiorespiratory fitness on the decrement in maximal aerobic power at high altitude. *Eur J Appl Physiol Med.* 1985;54:12–15.

letes. Even acknowledging the problems with accuracy and sensitivity of $\dot{V}O_2$max measurement techniques,[39] these and other data presented in Figure 22-1 suggest that small declines in $\dot{V}O_2$max begin at a much lower altitude than had been previously assumed by Buskirk and colleagues[42] and by Grover, Weil, and Reeves.[43] In addition, it would appear from Figure 22-1 that there is a more rapid, nonlinear decline in $\dot{V}O_2$max at altitudes in excess of approximately 6,300 m. This more rapid decline may be linked with reduced blood flow, reduction of muscle mass, or metabolic deterioration, conditions that in any combination are often associated with chronic hypoxic exposure.[60,63–66]

Fitness Level and Maximal Aerobic Power Variability

The subgroupings in Figure 22-2 to Figure 22-5, separate discussions of which follow, were limited to the factors of fitness level, prealtitude exposure elevation, gender, and altitude duration, respectively. Other factors such as age or smoking status could not likewise be assessed because of a paucity of published reports at altitude on such topics. The intent is not to present a broad statistical relationship but rather to provide an appreciation and perspective of the wide range of factors that modify the decrement in $\dot{V}O_2$max that occurs with altitude exposure.

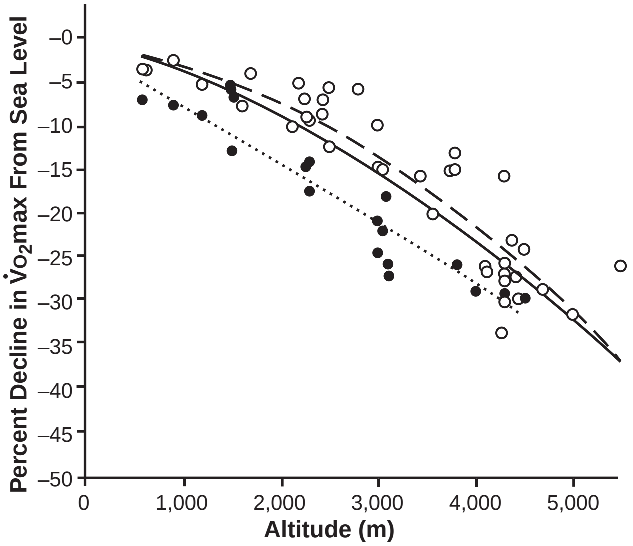

Fig. 22-2. The effect of fitness level on the variability of the decrement of $\dot{V}O_2$max is depicted in studies of highly conditioned (baseline altitude $\dot{V}O_2$max was ≥ 63 mL/kg/min, closed circles)[*] and less-well-conditioned ($\dot{V}O_2$max was ≤ 51mL/kg/min, open circles)[†] individuals**.** Only mean data points based on objective fitness criteria (ie, $\dot{V}O_2$max normalized to body weight and measured at the preexposure, resident altitude) are included. Studies that used only descriptive terms such as "highly fit," "well-conditioned," or "trained" to characterize subjects were not included. To minimize possible confounding effects of altitude acclimatization and/or physical conditioning changes due to training while at altitude, data collected beyond the first 3 days of altitude exposure were also excluded. Regression lines for the highly conditioned (dotted line) and less-well-conditioned (dashed line) individuals, as well as the database regression line (solid line), which is redrawn from Figure 22-1 but truncated at 5,500 m altitude, are included. Reproduced with permission from Fulco CS, Rock PB, Cymerman A. Maximal and submaximal exercise performance at altitude. *Aviat Space Environ Med.* 1998;67(8):794.
Sources for the data points for highly conditioned[*] and less-well-conditioned[†] individuals are found in the Attachment at the end of this chapter.

Figure 22-2 indicates that highly fit (≥ 63 mL/kg/min) individuals (represented in the graph by closed circles) generally have a larger decrement in $\dot{V}O_2$max at altitude than less fit (≤ 51 mL/kg/min) individuals (open circles). Although the data presented were dichotomized to compare widely differing fitness levels, the amount of decline in $\dot{V}O_2$max at a given altitude is inversely related to the degree of fitness, but within a much narrower range than is apparent in Figure 22-2, and seems to exist on a continuum.[67–69] For example, Young, Cymerman, and Burse[68] compiled data from several studies that used a relatively homogeneous group of subjects (51 young, male soldiers) whose values for sea-level $\dot{V}O_2$max were normally distributed from 36 to 60 mL/kg/min. In those studies, the $\dot{V}O_2$max decrement at 4,300 m altitude was greater for the more highly fit subjects ($\dot{V}O_2$max decrement = $\dot{V}O_2$max decrement = 0.52 – 11.39 • $\dot{V}O_2$max [sea level], $r = 0.56$, $P < .05$). At extreme altitudes (> 7,000 m), however, there is some evidence suggesting that the difference in $\dot{V}O_2$max decrement owing to fitness levels diminishes.[60] Nevertheless, the collective results indicate that much of the variability in $\dot{V}O_2$max decrement at altitudes up to at least 5,500 m is closely associated with prealtitude exposure fitness levels. Of the studies used to prepare Figure 22-2 that directly compared high with moderate-to-low fitness levels,[49,58,67,70] the greater $\dot{V}O_2$max decrement in the more-fit subjects was associated with pulmonary gas–exchange limitations, evidenced by lower arterial blood saturations that were exacerbated during hypoxic exercise (see Chapter 21, Human Adaptation to High Terrestrial Altitude).

Prealtitude Exposure Elevation and Maximal Aerobic Power Variability

Figure 22-3 demonstrates that the regression lines of the prealtitude exposure elevation—the elevation where experimental, prealtitude exposure baseline data were collected—lower than 100 m do not differ meaningfully from the database regression line. However, mean values for prealtitude exposure elevations higher than 400 m tend to fall above the low baseline altitude and the database regression lines, especially in the range of 2,200 m to 4,300 m altitude. Therefore, the potential $\dot{V}O_2$max decrement measured at any altitude would be lessened if experimental, prealtitude exposure baseline data are

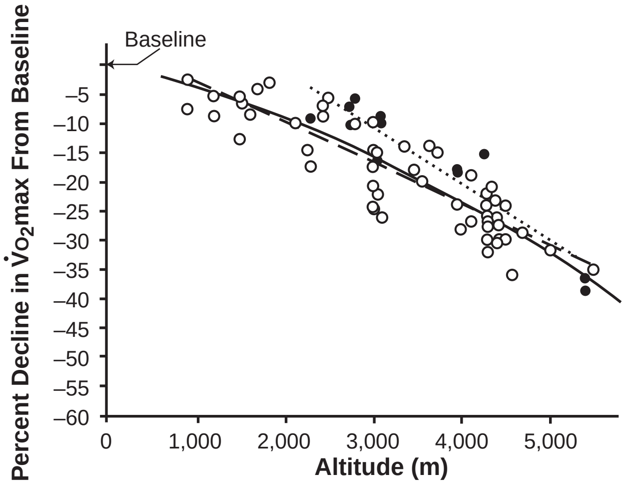

Fig. 22-3. The effects of a difference in prealtitude exposure elevations on $\dot{V}O_2$max decrement variability are shown from two subgroupings of studies: those whose baseline resident altitudes were lower than 100 m (open circles)* and those whose baseline resident altitudes were higher than 400 m (closed circles).† Regression lines were calculated for the lower baseline-resident elevations (dashed line) and higher baseline-resident elevations (dotted line) and compared with the database regression line (solid line), which is redrawn from Figure 22-1 but truncated at 5,500 m altitude. To minimize possible confounding effects of changes due to altitude acclimatization and/or physical conditioning while residing at the experimental altitude, only data collected within the first 3 days of hypobaric hypoxia or during hypoxic gas breathing were included. Reproduced with permission from Fulco CS, Rock PB, Cymerman A. Maximal and submaximal exercise performance at altitude. *Aviat Space Environ Med.* 1998;67(8):795.

Sources for the data points for baseline resident altitudes < 100 m* and > 400 m† are found in the Attachment at the end of this chapter.

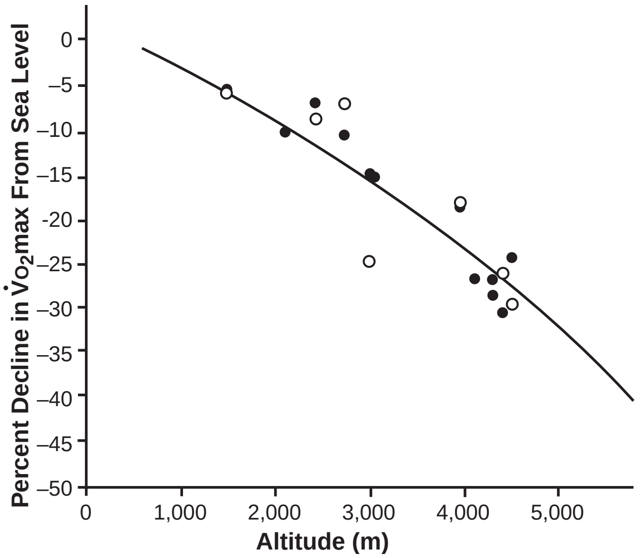

Fig. 22-4. Gender comparison of the $\dot{V}O_2$max decrement at altitude. Data were derived from seven studies* in which $\dot{V}O_2$max decline was reported for women (closed circles) during altitude exposure or during hypoxic gas mixture breathing. Also included are the mean results for men (open circles) from the four of these studies† in which direct gender comparisons were made. Data are plotted against the database regression line of Figure 22-1, truncated at 5,500 m. For all seven studies, $\dot{V}O_2$max was measured within an hour of altitude exposure or hypoxic gas mixture breathing. Reproduced with permission from Fulco CS, Rock PB, Cymerman A. Maximal and submaximal exercise performance at altitude. *Aviat Space Environ Med.* 1998;67(8):796.

Sources for the data points for women* and men† during altitude exposure or breathing hypoxic gas mixtures are found in the Attachment at the end of this chapter.

collected at elevations of 400 m or higher. These data indicate that some of the interstudy variability observed in $\dot{V}O_2$max decrements at a given higher altitude is likely due to differences in the elevation where the prealtitude exposure baseline values were obtained.

Gender and Maximal Aerobic Power Variability

Data presented in Figure 22-4 suggest there is no difference between men and women in the percentage of $\dot{V}O_2$max decrement at altitude; both genders had similar decrements compared with the database regression line of Figure 22-1. In addition, the only reported altitude study controlling for menstrual cycle phase[71] indicated that the $\dot{V}O_2$max decline from sea level to 4,300 m was not significantly different between early follicular and midluteal cycle phases or different from the database regression line, indicating little, if any, effect of cycle menstrual cycle phase.

Altitude Exposure Duration and Maximal Aerobic Power Variability

In Figure 22-5, data from chronic (> 10 d) altitude studies or exercise training studies and acute (< 2 h) hypoxic-exposure studies were compared, in an effort to provide a means to assess increases in variation due to changes in physical conditioning at altitude, altitude acclimatization, or both. The mean decline in the acute altitude-exposure studies lies within two standard deviations of the regression line of the database (see Figure 22-1), while

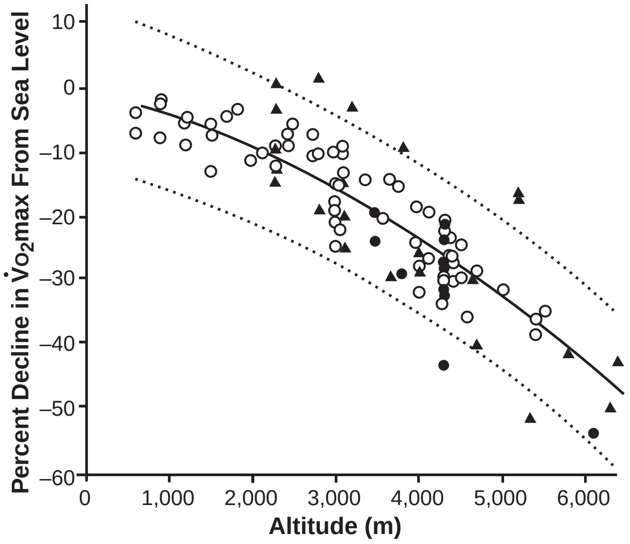

Fig. 22-5. Athletic training, trekking expeditions, and altitude acclimatization all affect the variability of $\dot{V}O_2$max decrement. The studies illustrated represent mean declines in $\dot{V}O_2$max during acute hypobaric hypoxia or hypoxic gas breathing (< 2 h, open circles),[*] altitude acclimatization (± 10 days, closed circles),[†] long-term altitude training,[‡] and trekking[§] (closed triangles). Also shown are the database regression line (——) and ± 2 SD lines (···). Reproduced with permission from Fulco CS, Rock PB, Cymerman A. Maximal and submaximal exercise performance at altitude. *Aviat Space Environ Med.* 1998;67(8):796.
[*]Sources for the data points for acute hypobaric hypoxia or hypoxic gas breathing,[*] altitude acclimatization,[†] long-term altitude training,[‡] and trekking[§] are found in the Attachment at the end of this chapter.

the mean decline of some of the chronic altitude-exposure studies falls within, and some outside, this range. The studies showing the least decline in mean $\dot{V}O_2$max during chronic exposures to altitudes of 5,200 m or lower were composed of subjects who were neither endurance athletes nor highly conditioned. It is likely that the subjects in these studies improved their fitness level while at altitude.[19,25,63]

The variability of the mean decrements in $\dot{V}O_2$max for exercise training studies involving chronic exposures and using highly conditioned subjects ($\dot{V}O_2$max was > 63 mL/kg/min)[24,27,28,45,72] was indistinguishable from that of the acute altitude-exposure studies (ie, the subjects maintained their fitness levels). Three other studies[60,66,73] of chronic altitude exposure had mean $\dot{V}O_2$max declines at or below the lower standard deviation range line. Two were nonexercise training studies[60,66] in which subjects became detrained owing to reduced activity levels at altitude; in one,[60] a reduced muscle mass was documented,[65] which may have reduced maximal exercise capabilities. The third study comprised members of a trekking expedition,[73] whose relatively poor performance during maximal testing likely also resulted from factors such as a reduced muscle mass.

The data presented in Figure 22-5 suggest that if the level of physical condition is not altered significantly by increases in activity or exercise training or by physical deterioration, the magnitude of decline in $\dot{V}O_2$max and the amount of variability at each altitude stays relatively constant during chronic compared with acute altitude exposure. In addition, the data from studies in which daily physical activity was light to moderate (and thus did not provide a sufficient training stimulus that resulted in a $\dot{V}O_2$max increase) do not support the concept that simply residing at altitude improves oxygen transport to an extent that improves $\dot{V}O_2$max.

Submaximal Exercise Performance

Oxygen uptake, or the "metabolic cost" for a particular exercise activity performed at a specified rate (ie, power output), is similar at sea level and altitude.[74–76] But because $\dot{V}O_2$max progressively declines with increasing elevation, a fixed power output represents a progressively greater *relative* exercise intensity (ie, a higher percentage of $\dot{V}O_2$max) as the elevation increases. The practical implication is that it is more difficult to perform submaximal exercise (or work) at a fixed power output at altitude than at sea level. The impairment will be most conspicuous in those activities in which a given distance must be traversed in the least amount of time (eg, a 5-km competitive race), or which involve sustained, arduous exercise that utilizes many muscle groups.[4,10,21,22,77,78] However, it is difficult to predict accurately both (*a*) the magnitude of an individual's submaximal exercise impairment from the $\dot{V}O_2$max decrement at altitude, and (*b*) an individual's likely success in exercise events or work activities relative to a similar group of individuals at altitude.[19,79,80]

One reason submaximal exercise performance decrements are hard to predict from the decline in $\dot{V}O_2$max is that $\dot{V}O_2$max measures only the maximal aerobic contribution, whereas exercise episodes of various intensities and durations involve differing proportions of aerobic and anaerobic processes.[26,40] A 400-m, 50-second lap for champion runners at sea level, for example, might require approximately 20% aerobic and 80% anaerobic processes; for a

1,500 m, 4-minute run, the proportion may be 60% to 40%; and for a 5-km, 14-minute run, 90% to 10%.[26,40] Moreover, at altitude, compared with at sea level, there is a reduction in the rate of reaching steady-state oxygen uptake[74,81] that effectively increases the anaerobic component for all distances, and further decreases the accuracy of predicting some submaximal exercise performance impairments. In addition, unlike the objectivity of the $\dot{V}O_2max$ "plateau" that indicates high motivation and assures maximal short-term effort,[38] there are no similar criteria for assuring submaximal exercise performance. Therefore, submaximal exercise performance differences due to changes in motivation levels or other factors (eg, such as lack of skill and experience; inability to tolerate pain[29]) are unaccounted for and may significantly but unquantifiably alter the final outcome. All these reasons are likely to induce at least as much variability in submaximal exercise performance at altitude as that associated with the $\dot{V}O_2max$ decrement (see Figure 22-1).

One factor that may benefit exercise performance in some athletic events at altitude is the lessened air resistance due to the reduced air density. At a typical exercise training altitude of 2,300 m, the 24% reduction in air density[80] increases the distances for field events such as the shot put by 6 cm, the hammer throw by 53 cm, the javelin by 69 cm, and the discus by 162 cm.[82] For running very short distances, in which there is a small aerobic component and high velocity, the advantage of a reduction in air resistance can result in faster times at altitude than at sea level.[20,22,83] For longer duration events such as 5-and 10-km runs, the small advantage afforded by the reduced air resistance is lessened in comparison with the larger impairment linked to the $\dot{V}O_2max$ reduction, and run times are slower than at sea level.[22,45,83] But for events such as speed skating and track cycling, in which velocities are much greater than in running, the reduced air resistance at altitude allows an improved performance compared with sea level.

Measuring submaximal exercise performance using laboratory testing paradigms (such as pedaling a cycle ergometer at a specific exercise intensity until volitional exhaustion) can reduce or eliminate variability due to the influences of wind resistance, skill, and experience (Figure 22-6). However, interindividual and intraindividual differences in motivation and pain tolerance still remain, especially for untrained individuals. One way to minimize such variability is to focus primarily on athletic performances during competitions. By using athletes, who represent a homogeneous group of people who are presumed to be healthy and highly motivated and who are performing at an "all-out" effort in precisely timed events for which they are trained, the effects of altitude exposure per se on submaximal exercise performance should be more readily apparent.

As can be seen in Figure 22-7, performances in maximal-effort events lasting less than 2 minutes at sea level are not adversely affected by altitude exposure. For events lasting 2 minutes or longer, however, the times to complete events (relative to sea-level performances) tend to increase with elevation. For events lasting 2 to 5 minutes, a mean performance decrement threshold occurs at approximately 1,600 m. For events lasting longer than 20 minutes, the threshold occurs at about 600 m to 700

Fig. 22-6. Exercise performance is being measured at a simulated altitude of 5,500 m. The subject is acclimatized and performing heavy exercise on a bicycle ergometer in the Hypobaric Chamber at the US Army Research Institute of Environmental Medicine, Natick, Mass. Note that the unacclimatized investigators must wear oxygen masks to enable them to work at this altitude.

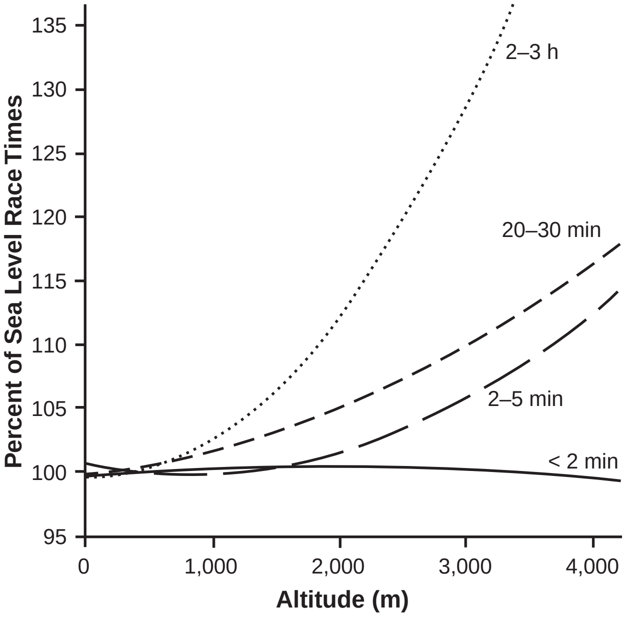

Fig. 22-7. Decrements in athletes' performance (as functions of event duration and altitude) are seen after 10 days of altitude training. The data are derived from several studies that reported results of highly conditioned athletes, primarily during running and swimming competitions,* who had lived and trained at altitude for at least 10 days immediately prior to competition. Altitude exposures lasting longer than 10 days were used in the analyses to minimize potentially confounding factors such as mountain sicknesses and nonfamiliarity with the altitude environment. The four regression lines were created using both individual and group data (not shown). They illustrate how sea-level performance would change for events lasting from less than 2 minutes to over 2 hours. For example, at 2,000 m altitude, events lasting less than 5 minutes at sea level would be minimally affected, while events lasting 20 to 30 minutes at sea level would be impaired by about 5%, and events lasting 2 to 3 hours would be impaired by 10% to 15%. Reproduced with permission from Fulco CS, Rock PB, Cymerman A. Maximal and submaximal exercise performance at altitude. *Aviat Space Environ Med.* 1998;67(8):797.

*Sources for the data points are found in the Attachment at the end of this chapter.

m, an altitude consistent with significant declines in $\dot{V}O_2$max for similar groups of highly trained subjects.[49,62] These data are consistent with the concept that the magnitude of impairment will be more closely linked to the $\dot{V}O_2$max decrement as the aerobic contribution of an event increases towards 100%. For example, events lasting 2 to 5 minutes at sea level will average about 2% longer at an altitude of 2,300 m; those lasting 20 to 30 minutes, 7% longer; and 2 to 3 hours, 17% longer (see Figure 22-2). At 2,300 m elevation, the mean percentage decline in $\dot{V}O_2$max would be expected to be approximately 15% for a similar group of highly conditioned athletes (see Figure 22-2). The approach used for this analysis can also be used for many military applications. For instance, the average 2-mile physical fitness test in personnel stationed at Fitzsimons Army Medical Center, Denver, Colorado (1,609 m), is increased by 5% (from about 16 to 17 min),[4] a value similar to the decrement that could be estimated from Figure 22-7.

Muscle Strength and Power

Muscle strength and maximal muscle power, determined by the force generated during a single, brief (1–5 sec), maximal muscle contraction (static or dynamic), are generally not adversely affected by acute or chronic altitude exposure[64,76,84–89] as long as muscle mass is maintained.[64,90,91] In addition, alpha-motoneuron excitability, nerve- and muscle-conduction velocity, and neuromuscular transmission are not impaired, even at altitudes exceeding 4,300 m.[76,88,92]

Unchanged maximal force and maximal power generation at altitude may relate to one or both of the following factors:

- maintenance of low resting levels of metabolites[74,91,94] that, if higher (as during more prolonged exercise), could potentially impair function of the contractile machinery[95,96]; and
- preservation of normal resting levels of high energy phosphates sufficient to support the rate of adenosine 5'-triphosphate (ATP) turnover (1–2 mmol/s) for brief maximal muscle performance.[97]

The amounts of ATP and phosphocreatine available at rest in humans prior to a maximal contraction are approximately 26 and 75 mmol/kg dry muscle, respectively.[93,98] Anaerobic performance[99,100] during very intense, maximal or supramaximal exercise (eg, the Wingate test) lasting 30 seconds are generally also not adversely affected at altitude.[90,101,102] For anaerobic performance assessments lasting longer than 30 seconds, there are conflicting results[90]; measurement inconsistencies of the delay and/or the rate of rise of $\dot{V}O_2$ may be contributory factors.[74,81]

PRACTICAL ASPECTS OF HUMAN PERFORMANCE AT ALTITUDE

The Effects of Altitude on Military Occupational Tasks

It is obvious that military personnel are involved in many physical activities other than athletic events (eg, running). Such activities are typically work- or mission-specific and can encompass extremely light to very demanding efforts that use different muscle groups for varying periods of time. In a sense, many work-related tasks have similarities to exercise performance in terms of effort intensity, volumes of active muscle involved, and activity duration. Therefore, the principles discussed above for exercise performance decrements at altitude also relate to decrements in work performance at altitude.

To illustrate the effects of altitude exposure on work performance, 42 tasks[78] were chosen from both the *Soldier's Manual of Common Tasks*, Skill Level 1, STP 21-1-SMCT, Department of the Army,[103] and the Military Occupational Specialty (MOS) Physical Task List, US Army Infantry School, Fort Benning, Georgia[104] (Exhibit 22-2 and Figure 22-8). The tasks are ranked by ascending order of metabolic cost ($\dot{V}O_2$, in mL/kg/min) and the percentage of $\dot{V}O_2$max required to perform the task as determined at sea level and estimated for 2,000 m to 6,000 m (estimates made from the database regression line in Figure 22-1) (Table 22-1). The altitude percentages were calculated with the assumptions that sea-level task intensity and duration were not altered and additional rest breaks were not provided. As can be seen, the percentage of $\dot{V}O_2$max required to complete each task increases progressively with ascending elevation. Note that some tasks (tasks 37 to 42) that are of submaximal intensity at sea level (60% to 70% of $\dot{V}O_2$max) require nearly maximal or greater than maximal oxygen uptakes at higher terrestrial elevations.

Practical Guidelines for Military Operational Planning at Altitude

Although Table 22-1 illustrates how an increase in elevation affects the relative intensity of specific military tasks, it provides little guidance as to modifications that could be made to increase the probability of successfully completing the tasks. Such modifications at altitude, compared with sea level, would include at least one of the following:

- an increase in task duration,
- a reduction in task intensity, or
- more-frequent rest breaks.

The specific amount and type of modification will depend on factors such as type of task involved, task difficulty, elevation, time at altitude, urgency, weather, terrain, and involved muscle mass (eg, arm or leg work). At present, precise adjustments for particular tasks for specific altitudes have not yet been established. Nevertheless, estimates for additional time to complete a task during initial altitude exposure can be made by using information provided by the National Institute for Occupational Safety and Health for lifting tasks, predominantly,[105] and Figure 22-7 for walking and carrying tasks, predominantly. Industrial recommendations stipulate that tasks requiring mostly lifting and less than 30% of $\dot{V}O_2$max can be performed for 2 to 8 hours; those requiring 40% of $\dot{V}O_2$max, 1 to 2 hours; and those requiring 50% or more of $\dot{V}O_2$max, 1 hour or less.[105] Using this information, the data in Table 22-1, task 24, for example, can be performed for 2 to 8 hours at sea level, 1 to 2 hours at 4,000 m, and less than an hour at 6,000 m. Similarly, data illustrated in Figure 22-7 indicate that if task 35 can be performed for 3 hours at sea level, then 30% additional time (about an hour) may have to be allowed at 3,000 m.

Time modifications such as those suggested above are an important means to compensate for impaired physical performance associated with the hypoxia of altitude exposure—especially during the first few days of exposure. With continued exposure, altitude acclimatization occurs and the additional difficulty of exercising and working are lessened. Numerous physiological changes associated with altitude acclimatization that occur to minimize the impact of hypoxia are discussed in Young and Young's chapter in *Human Performance Physiology and Environmental Medicine at Terrestrial Extremes*.[75] Briefly, with initial altitude exposure, arterial oxygen content (CaO_2) is reduced. But for any specified submaximal exercise or work intensity, oxygen transport to the working muscles is maintained because of a compensatory increase in cardiac output. In other words, cardiac output at a given submaximal exercise or work intensity will be greater during initial altitude exposure than at sea level. For maximal levels of exercise or work, maximal cardiac output cannot increase to levels greater than those at sea level, and thus can not compen-

EXHIBIT 22-2

FORTY-TWO SOLDIER TASKS, RANKED IN ORDER OF METABOLIC COST

1. Prolonged standing on a circulation control point: Task #3, MOS 95B (Military Police), Skill Level 1-3. Wearing combat equipment (LBE), stand in place for 15 min.
2. Lift 105-mm projectiles: Task #4, MOS 55D (Missiles/Munitions), Skill level 1-5. Carry 25-kg projectiles 15 m and lift to the height of a 2.5-ton truck (1.32 m), once every 2 min for 15 min.
3. Relocate/establish operations: Task #1, MOS 33S (Intelligence), Skill Level 1-5. Lower/lift 25-kg box to/from ground level from/to the height of a 2.5-ton truck (1.32 m), once every 4 min for 15 min (lift every 2 min/lower every 2 min).
4. Perform emergency destruction operations: Task #24, MOS 16B (Air Defense Artillery), Skill level 1-4. Lift a 6.8-kg shape charge, carry 15 m, and hold at fullest upward reach for 1 min; repeat every 2 min for 15 min.
5. Relocate/establish operations: Task #2, MOS 33S (Intelligence), Skill level 1-5. Lift 22-kg box to the height of a 2.5-ton truck (1.32 m), once per minute for 15 min.
6. Lift 105-mm projectiles: Task #4, MOS 55D (Missiles/Munitions), Skill level 1-5. Carry 25-kg projectiles 15 m and lift to the height of a 2.5-ton truck (1.32 m), once per minute for 15 min.
7. Receive nonperishable subsistence; unload 40-ft container: Task #1, MOS 76X (Quartermaster), Skill Level 1-4. Lift 18-kg ration containers from the floor to 0.9 m and carry 6.1 m, once per minute for 15 min.
8. Relocate/establish operations: Task #1, MOS 33S (Intelligence), Skill Level 1-5. Lower/lift 25-kg box to/from ground level from/to a 2.5-ton truck, once per minute for 15 min (lift every 30 s, then lower every 30 s).
9. Load crates of explosives onto truck: Task #5, MOS 12B (Engineers), Skill level 1-2. Lift a 27.3-kg crate, carry it 4 m, and load it onto a 2.5-ton truck (1.32 m), once per minute for 15 min.
10. Relocate/establish operations: Task #2, MOS 33S (Intelligence), Skill level 1-5. Lift a 22.7-kg box to the height of a 2.5-ton truck (1.32 m), twice per minute for 15 min.
11. Maintain an M16A1 Rifle: Common Task #071-311-2025. Assemble/disassemble the weapon three to five times for a duration of 5-10 min.
12. Rig a supply load on a modular platform for airdrop: Task #1, MOS 43E (Quartermaster), Skill Level 1-5. Lift a 36-kg ammunition box from ground level to a height of 0.9 m and carry it 6.1 m, once per minute for 15 min.
13. Load artillery pieces in preparation for firing: Task #8, MOS 13B (Field Artillery), Skill Level 1-2. Lift 45-kg projectiles to 1.7 m and carry 5 m, twice per minute for 15 min.
14. Move by foot: Task #1, MOS 11B (Infantry), Skill Level 1-5. Wearing combat equipment (LBE) without a rucksack, march on a level, hard surface at 1.11 m/s for 15 min.
15. Lift, carry, and move patients: Task #7, MOS 91B (Medical), Skill Level 1-2. Given a two-person litter team, move a patient weighing 68 kg over level terrain a distance of 500 m in 20 min.
16. Move by foot: Task #1, MOS 11B (Infantry), Skill Level 1-5. Wearing combat equipment with a 20-kg rucksack, march on a level, hard surface at 1.11 m/s for 15 min.
17. Lift 105 mm Projectiles: Task #2, MOS 55D (Missile/Munitions), Skill Level 1-5. Lift a 25-kg projectile and carry it 15 m at the height of 2.5-ton truck (1.32 m), twice per minute for 15 min.
18. Unload and stack paper stock: Task #2, 74B (Administration), Skill Level 1-2. Lift an 18.2-kg box and carry it 9 m, to include up stairs 2.5 m high, once per minute for 15 min.
19. Move by foot: Task #1, MOS 11B (Infantry), Skill Level 1-5. Wearing combat equipment (LBE) with a 30-kg rucksack, march on a level, hard surface at 1.11 m/s for 15 min.
20. Load artillery pieces in preparation for firing: Task #8, MOS 13B (Field Artillery), Skill Level 1-2. Lift 45-kg projectiles to 1.7 m and carry 5 m, three times per minute for 10 min.
21. Move by foot: Task #1, MOS 11B (Infantry), Skill Level 1-5. Wearing combat equipment (LBE) without a rucksack, march on a level, hard surface at 1.48 m/s for 15 min.
22. Move by foot: Task #1, MOS 11B (Infantry), Skill Level 1-5. Wearing combat equipment (wt: 7 kg), carrying an M-16 (wt: 3 kg), and a 30-kg rucksack, march on a level, hard surface at 1.11 m/s for 15 min.

(**Exhibit 22-2** *continues*)

Exhibit 22-2 *continued*

23. Relocate/establish operations: Task #1, MOS 33S (Intelligence), Skill Level 1-5. Lift 22.7-kg box to height of a 2.5-ton truck (1.32 m), four times per minute for 15 min.
24. Relocate/establish operations: Task #2, MOS 33S (Intelligence), Skill Level 1-5. Lift/lower 22.7-kg box to/from 2.5-ton truck (1.32 m), 6x/min for 10 min (lift in 10 s; then lower in 10 s).
25. Dig individual defensive position: Task #11, MOS 11 B (Infantry), Skill Level 1-5. Using entrenching tool, dig a foxhole 0.45-m deep, approximately 0.6 m wide x 1.8 m long, in sandy soil in 30 min.
26. Load artillery pieces in preparation for firing: Task #8, MOS 13B (Field Artillery), Skill Level 1-2. Lift 45-kg projectiles to 1.7 m and carry 5 m, four times per minute for 10 min.
27. Move by foot: Task #1, MOS 11B (Infantry), Skill Level 1-5. Wearing combat equipment with a 20-kg rucksack, march on a level, hard surface at 1.48 m/s for 15 min.
28. Move by foot: Task #1, MOS 11B (Infantry), Skill Level 1-5. Wearing combat equipment (LBE) with a 20-kg rucksack, march in loose sand at 0.98 m/s for 15 min.
29. Employ hand grenades: Common Task #071-325-4407. Using dummy grenades, engage a 5-m–radius target, 40 m from a covered position, three times per minute for 10 min.
30. Move by foot: Task #1, MOS 11B (Infantry), Skill Level 1-5. Wearing combat equipment (LBE) with 30-kg rucksack, march on a level, hard surface at 1.48 m/s for 15 min.
31. Lift 105-mm projectiles: Task #4, MOS 55D (Missiles/Munitions), Skill Level 1-5. Lift a 25-kg projectile and carry it 15 m to the height of a 2.5-ton truck (1.32 m), four times per minute for 15 min.
32. Carry TOW equipment: Task #1, MOS 11H (Infantry), Skill level 1-4. Wearing combat equipment (LBE), carry a 24.5-kg traversing unit up a grade (10%), at 0.89 m/s for 15 min.
33. Lift, carry, and move patients: Task #7, MOS 91B (Medical), Skill Level 1-2. Given a four-person litter team, move a patient weighing 81.8 kg over level terrain a distance of 1,000 m in 30 min.
34. Lift, carry, and move patients: Task #7, MOS 91B (Medical), Skill Level 1-2. Given a two-person litter team, move a patient weighing 68.2 kg, 100 m every 90 s for 10 min.
35. Move by foot: Task #1, MOS 11B (Infantry), Skill Level 1-5. Wearing combat equipment (wt: 7 kg) and carrying a weapon (wt: 3 kg) with a 30-kg rucksack, march on a level, hard surface at 1.48 m/s for 15 min.
36. Lift, carry, and move patients: Task #7, MOS 91B (Medical), Skill Level 1-2. Given a two-person litter team, carry a patient weighing 68.2 kg for 27.5 m, lift to the height of a 2.5-ton truck (1.32 m), then return 27.5-m to retrieve the next patient; complete 10 cycles in 10 min.
37. Move over, through, and around obstacles: Common Task #071 326-0503. Wearing combat equipment (LBE), traverse a 150-m obstacle course in 2 min at a constant rate; complete 5 cycles in 10 min.
38. Move by foot: Task #1, MOS 11B (Infantry), Skill Level 1-5. Wearing combat equipment (LBE) with a 20-kg rucksack, march in sand at 1.31 m/s for 15 min.
39. Move under direct fire (rush and crawl): Common Task #071-326 0502. Wearing combat equipment (LBE) and carrying a weapon, conduct high crawl and rush maneuvers over wooded terrain; complete 136.5-m course in 90 s; repeat five times.
40. Move by foot: Task #1, MOS 11B (Infantry), Skill Level 1-5. Wearing combat equipment (LBE) without a rucksack, move on a level, hard surface at 2.24 m/s for 10 min.
41. Carry TOW equipment: Task #1, MOS 11B (Infantry), Skill Level 1-4. Wearing full combat equipment, carry a 24.5-kg traversing unit up a grade (20%), at 0.89 m/s for 15 min.
42. Carry an M5 smoke pot in preparation of a smoke line: Task #1, MOS 54C (Chemical), Skill Level 1-2. Lift two 13.6 kg smoke pots, carry 30 m, and then lower the smoke pots, four times per minute for 10 min.

LBE: load-bearing equipment
TOW: tube-launched, optically tracked, wire-guided (missile system)
Adapted from Patton JF, Murphy MM, Bidwell TR, Mello RP, Harp ME. *Metabolic Cost of Military Physical Tasks in MOPP 0 and MOPP 4.* Natick, Mass: US Army Research Institute of Environmental Medicine; 1996. USARIEM Technical Report T95-9: 5–9.

sate for the reduced CaO_2. The result is a reduction in maximal oxygen transport and $\dot{V}O_2$max. With sustained exposures of 2 to 3 weeks, CaO_2 increases toward sea-level values, owing to both hemoconcentration due to the loss of plasma volume and an increase in arterial oxygen saturation (SaO_2).

Fig. 22-8. Lift, carry, and move patients (MOS 91B, task 33; see Exhibit 22-2). A four-person litter team is moving an 81.8-kg patient over level terrain at a rate of 305 m/30 min. The energy cost of this task would require approximately 46%, 53%, and 66% of $\dot{V}O_2$max at sea level, 3,000 m, and 5,000 m, respectively.

As a consequence of the decreased plasma volume, however, stroke volume and cardiac output are both reduced. During submaximal levels of exercise or work, the restored CaO_2 compensates for the reduced cardiac output such that oxygen transport to the working muscles is maintained. But during maximal levels of exercise or work, the restored CaO_2 cannot compensate for the altitude-induced decline in maximal cardiac output, and maximal oxygen transport and $\dot{V}O_2$max do not improve.[43,106]

Additionally, many other ventilatory, hematological, and metabolic adaptations may aid oxygen transport and improve exercise capabilities or military task performance. Some of these may include increases in 2,3-diphosphoglycerate (2,3-DPG) concentration,[54] muscle capillary proliferation,[107] oxidative enzymes,[108] myoglobin,[108] usage of free fatty acids,[109] buffering capacity,[107] oxygen deficit,[107] and decreased ammonia accumulation[66] and dependence on muscle glycogen.[109] These hypoxia-produced changes in oxygen delivery and metabolic profile have been suggested by many within the scientific and athletic communities as a potential means of inducing an additive or potentiating effect on exercise performance—not only at altitude but also on return to sea level. Before we review and summarize the results of such information, it is important that we describe exercise training fundamentals and experimental study considerations. Doing so will allow a more accurate appraisal of the postulate that exercise training or living, or both, under hypoxic conditions enhances $\dot{V}O_2$max and other measures of exercise performance, compared with both living and training at sea level.

Training Strategies for Improving Exercise Performance at Altitude

A plethora of information exists about how various combinations of exercise stimuli—intensity, duration, and frequency—can improve both $\dot{V}O_2$max and submaximal exercise performance at sea level.[110–114] In general, that information suggests that the higher the exercise intensity, the longer the exercise duration, the more frequent the training sessions, and the lower the initial fitness level, the greater will be the performance improvements.[114,115] The exercise training stimuli required to continue producing salutary effects increases as physical conditioning improves.[40,114,115] Therefore, the training stimuli for newly conditioned or highly conditioned individuals must necessarily be greater than for those less conditioned. For this reason, the same absolute training stimuli should not be used for all participants in an exercise training program but should be adjusted to accommodate each individual's current level of conditioning. Not maintaining exercise intensity, duration, and/or frequency of training can result in declines in $\dot{V}O_2$max and submaximal exercise performance.[111–114] Exercise training intensity, however, appears to be the principal stimulus.[111]

As stated above in the discussion of submaximal exercise, exercise at altitude, performed at the same power output as at sea level, represents a higher relative exercise intensity. During training at altitude, a higher exercise intensity may not be desirable because of issues such as not being able to sustain a given task for a required duration. Therefore, to maintain a comparable relative exercise intensity at altitude as at sea level, power outputs must be reduced during exercise training at altitude. However, reducing power output may result in relative deconditioning[23,36] that may offset any potential altitude-induced physiological benefits. Whether an altitude exercise training regimen will be successful in improving exercise performance more at altitude than at sea level would seem, then, to be the net result of a complex interaction of conditioning level, training stimuli, deconditioning, altitude acclimatization, and level of hypoxia.

For research purposes, it is also important to note that unless a matched group of individuals (ie, control group) train similarly while residing at sea level, it is difficult to assess the relative contributions of exercise training or detraining from the effects of hypoxia or altitude acclimatization. In addition, research studies may report only the assessment of $\dot{V}O_2$max in evaluating exercise training or hypoxia-induced results. If a subject's $\dot{V}O_2$max does not im-

TABLE 22-1

PERCENTAGE OF MAXIMAL AEROBIC POWER FOR 42 MILITARY OCCUPATIONAL TASKS AT INCREASING ALTITUDES

		% $\dot{V}O_2$max					
Task	$\dot{V}O_2$ (mL/kg/min)	SL[1]	2,000 m altitude[2]	3,000 m altitude[2]	4,000 m altitude[2]	5,000 m altitude[2]	6,000 m altitude[2]
1	4.9	9	10	11	12	13	16
2	6.7	13	14	15	16	18	22
3	6.7	12	14	15	16	18	22
4	7.4	14	15	16	18	20	24
5	7.5	15	15	17	18	21	24
6	8.5	16	17	19	21	23	27
7	9.1	18	19	20	22	25	29
8	9.5	18	19	21	23	26	31
9	9.6	18	20	21	23	26	31
10	9.8	19	20	22	24	27	32
11	11.0	20	22	24	27	30	35
12	11.0	21	22	24	27	30	35
13	11.0	21	22	24	27	30	35
14	11.8	21	24	26	29	33	38
15	12.0	22	24	27	29	33	39
16	12.2	24	25	27	30	34	39
17	12.4	23	25	28	30	34	40
18	13.7	25	28	31	33	38	44
19	13.9	27	28	31	34	38	45
20	14.0	27	29	31	34	39	45
21	14.4	28	29	32	35	40	46
22	15.2	29	31	34	37	42	49
23	15.4	29	31	34	37	42	50
24	16.5	30	34	37	40	45	53
25	17.1	33	35	38	42	47	55
26	17.4	34	35	39	42	48	56
27	18.1	33	37	40	44	50	58
28	19.1	37	39	43	46	53	62
29	19.7	36	40	44	48	54	64
30	21.1	41	43	47	51	58	68
31	22.9	45	47	51	56	63	74
32	23.2	44	47	52	56	64	75
33	23.9	46	49	53	58	66	77
34	24.6	47	50	55	60	68	79
35	25.7	48	52	57	63	71	83
36	27.0	52	55	60	66	74	87
37	29.5	58	60	66	72	81	95
38	29.7	59	60	66	72	82	96
39	30.3	59	62	67	74	83	98
40	33.5	62	68	75	82	92	108
41	39.0	75	79	87	95	107	126
42	41.4	76	84	92	101	114	134

SL: sea level

Data sources: (1) Patton JF, Murphy MM, Bidwell TR, Mello RP, Harp ME. *Metabolic Cost of Military Physical Tasks in MOPP 0 and MOPP 4.* Natick, Mass: US Army Research Institute of Environmental Medicine; 1996. USARIEM Technical Report T95-9. (2) Estimated from the database regression line in Figure 22-1.

prove, some of these studies may conclude that the altitude exposure and/or the exercise training regimen had no effect. This interpretation is questionable because significant improvements may occur in the response to standard submaximal endurance tests and during athletic performances with or without an increase in $\dot{V}O_2$max.[33,40,47,114,116,117]

Given the above considerations, findings based on appropriately controlled studies[30,45,118] support a beneficial effect of altitude training for altitude, but not subsequent sea-level performances (to be discussed below). In contrast, many anecdotal reports based on the practical experiences of coaches and athletes indicate that altitude exercise training—especially for elite endurance athletes—is not only beneficial but may be required for optimal performance at sea level.[47,119–123] This belief is so strong that it has stimulated a proliferation of moderate altitude (1,500–2,800 m) training sites and facilities around the world.[119,121]

The reasons for the dissimilar conclusions between the research and athletic communities with regard to the efficacy of altitude training for subsequent sea-level exercise performance are not readily apparent. Perhaps laboratory studies that assess changes in exercise performance do not provide an adequate basis for the assessment of specific athletes in competitive athletic events.[19,28,79,80,124] Exercise performance based solely on changes on laboratory estimates of $\dot{V}O_2$max, for example, may miss improvements in anaerobic capacity[107] that could result in improved track and field performances. Also, the level of athletic skill and judgment necessary for athletic success may not be adequately accounted for in the laboratory.[29] Or perhaps altitude training may be beneficial for some athletes but not others.[26,42,124] If so, then small individual improvements in athletic performance—enough to achieve competitive success—may be undetectable by the usual scientific statistical analyses that tend to assess only overall group changes.[125] It may also be that better results could result from

- a strong commitment to train harder at altitude than at sea level,
- training with the best athletes and coaches available,
- an athletic event's being perceived as easier on return to sea level, and
- the belief of athletes and coaches that altitude (or hypoxia) exercise training *does* provide an advantage.

Given these considerations, the following four sections assess the efficacy of residence or exercise training, or both, at altitude or sea level for the enhancement of exercise performance. In each section, a table presents studies from the literature that test the hypothesis that training or living or both under hypoxic conditions enhances $\dot{V}O_2$max, submaximal endurance exercise performance, and other measures of exercise performance compared to both living and training at sea level. Taken together, these studies also provide an appreciation of the complex interaction of the numerous factors that contribute to the lack of consensus about the efficacy of using hypoxia as a exercise performance enhancing aid. The studies selected represent a large sampling of the available exercise training studies that were conducted at different altitudes (1,300 m to 5,700 m), different training and residence durations (12 d–19 wk), and using civilian and military volunteer subjects with a range of fitness levels (mean sea-level $\dot{V}O_2$max values ranging from 37 to 74 mL/kg/min).

Hypoxic Exercise Training During Altitude Acclimatization

Table 22-2 presents studies that evaluated exercise performance of subjects who trained while residing at altitude. Of the 13 studies that lack control groups, seven reported a significant increase in $\dot{V}O_2$max either at altitude or on return to sea level. Of the four studies that included an exercise control group, none reported an improvement in $\dot{V}O_2$max—during or after altitude training—that could not be accounted for by the sea-level control group. The reason for the difference in findings between the studies with and without control groups cannot be attributed to differences in training altitudes, training durations, or subject fitness levels. Collectively, the results of these studies indicate that improvements in $\dot{V}O_2$max may occur during training while residing at altitude and that the higher $\dot{V}O_2$max may be retained on return to sea level. However, the improvement in $\dot{V}O_2$max likely results from exercise training alone and not to physiological changes associated with altitude acclimatization.

Conversely, maximal effort exercise performance at altitude for events lasting longer than 2 minutes can improve during altitude acclimatization independently of an increase in either training intensity or $\dot{V}O_2$max. Figure 22-9 shows data from elite athletes who were highly trained prior to altitude exposure and whose race times were recorded in the conduct of their primary event at the beginning and the end of their altitude exposure. Because of their high fitness levels and relatively short evaluation–reevaluation intervals, the improvement in athletic performance at altitude was not likely due to an increase in training. This conclusion is consistent with other controlled studies that show that altitude exposure with only maintenance training improves endurance performance, with[116] or without[33] an increase in $\dot{V}O_2$max.

Studies that have specifically assessed whether altitude exercise training during residence at altitude improves subsequent sea-level $\dot{V}O_2$max and maximal effort endurance exercise performance in the same subjects have produced conflicting or inconclusive results, however. On return to sea level, either both $\dot{V}O_2$max and athletic performance did not improve,[27,45] or both $\dot{V}O_2$max and athletic performance improved,[19,47] or $\dot{V}O_2$max did not improve but athletic performance did.[107,126] The reason or reasons for these conflicting results is not clear, but it probably is not related to differences in the level of prealtitude exposure fitness levels because the subjects in these studies were all highly conditioned. Differences in results may be related to a complex interaction of factors that include interstudy differences in exercise intensity, altitude duration, or types of exercise performance evaluations used, in any combination, and also to interindividual differences in training responsiveness. In addition, it should be noted that a small, statistically nonsignificant, training-induced improvement in mean $\dot{V}O_2$max (often reported as "no change") can result in a significant increase in submaximal exercise performance. For example, a 1% to 3% rise in $\dot{V}O_2$max results in a 12% to 45% improvement in endurance time to exhaustion.[33,48,117] These studies emphasize the importance of (1) not using $\dot{V}O_2$max as the sole criteria to judge the efficacy of an altitude training program, and (2) reporting individual rather than only group data for *both* $\dot{V}O_2$max and other measures of submaximal exercise performance, as some individuals may benefit from altitude training while others may not.

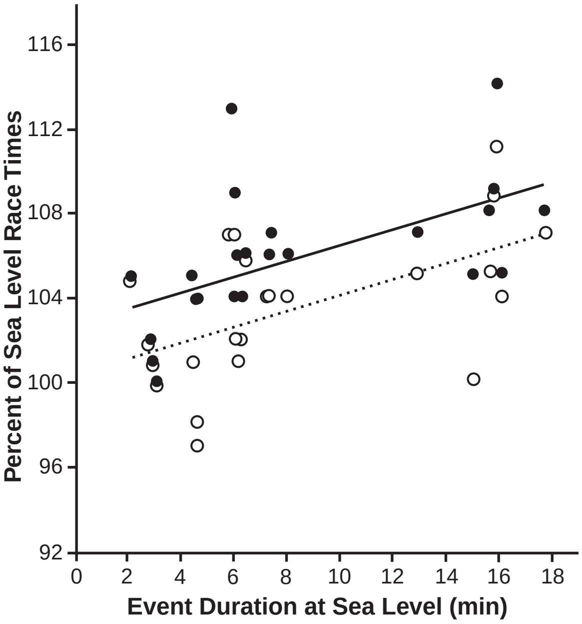

Fig. 22-9. The effect of training at altitude on performance at altitude (2,240 m to 2,800 m). The X axis is the event duration at sea level and the Y axis is the percentage change from the sea-level performance. Data* are from eight of the studies used to develop Figure 22-5. The data used in the graph above are for the same individuals and events but for two different altitude durations: acute exposures (< 5 d, closed circles) and chronic exposures (> 10 days, open circles). The regression lines depict the acute (solid line) and chronic (dashed line) exposure. Reprinted with permission from Fulco CS, Rock PB, Cymerman A. Maximal and submaximal exercise performance at altitude. *Aviat Space Environ Med.* 1998;67(8):798.
*Sources for the data points are found in the Attachment at the end of this chapter.

Hypoxic Exercise Training Without Altitude Residence

Short-duration hypobaric chamber studies or studies utilizing hypoxic gas mixtures during exercise training address the effects of training under repeated acute hypoxic conditions without inducing some of the physiological changes associated with altitude acclimatization such as increased hemoglobin and hematocrit concentrations,[56,127,128] and a reduction in maximal cardiac output.[43,75] Submaximal endurance exercise training during repeated short-duration hypoxic exposures may also enhance peripheral changes such muscle fiber size,[129] capillary density,[129,130] myoglobin concentration,[108] muscle oxidative capacity,[108] glycolytic activity,[108] and interfibrillar mitochondrial volume density[129]—but it has been difficult to determine from the reported data if the magnitude of these potentially salutary changes are greater during hypoxia training than during similar sea-level training.

The collective findings of the studies in which subjects trained daily for short periods at altitude or in hypoxia, but lived at sea level, are presented in Table 22-3. Improvements in $\dot{V}O_2$max were reported for some studies during testing in hypoxia[56,128–132] or normoxia,[66,128,131,132] whether or not control groups were used. In another study,[130] work capacity (ie, the total amount of aerobic work performed during an exhaustive incremental test) but not $\dot{V}O_2$max improved more for the experimental group than for the control group—but in hypoxia

TABLE 22-2

HYPOXIC EXERCISE WITH ALTITUDE ACCLIMATIZATION

Data Source	Training Altitude	Duration	Fitness (mL/kg/min)	Control Group?	$\dot{V}O_2$max Improvement at Altitude	$\dot{V}O_2$max Improvement on Return	Comments
1	2,300 m	10 d	?	No	+ 6%	+ 8%	Anaerobic capacity and 400-m run time not affected.
2	3,800 m	5 wk	37	No	+ 4%	+ 14%	—
3	3,475 m	20 d	44	No	0%	0%	Training not specified; no advantage of residing at 1,610 m altitude on 3,475-m performance.
4	2,300 m	23 d	?	No	+ 2%	+ 9%	Pre- to postaltitude 275-m, 1,609-m, and 3,218-m run times, but not swim times, improved.
5	4,300 m	12 d	48	No	0% (assumed)	n/a	45% increase in endurance time to exhaustion.
6	4,300 m	16 d	51	No	+ 10%	n/a	60% increase in endurance time to exhaustion.
7	4,000 m	55 d	63	No	+ 3%	0%	Greatly reduced exercise intensity at altitude. Altitude endurance performance equaled sea level control time after 20 d. No pre-to-post altitude difference in 400-m, 800-m, 1,609-m, and 3,218-m run times. Detraining effect was postulated.
8	2,270 m	4 wk	65	No	+ 5%	n/a	Improved $\dot{V}O_2$max, and 1,609 m and 4,828 m run times at altitude.
9	2,250 m	19 d	> 60 ?	No	+ 5%	n/a	4 weeks minimum altitude adaptation.
10	2,300 m–4,300 m	Varying durations	≥ 60	No	0%	0%	Some 1,609-m and 4,828-m run times improved at altitude.
11	2,300 m	Alternate training (1–2 wk) at sea level with training at atitude	74	No	+ 4%	+ 4%	Rigorous altitude training. 1,609-m and 3,218-m time trials improved at altitude and at return to sea level. Many personal best times.
12	3,090 m	17 d	72	No	+ 2%	+ 4%	—
13	2,700 m	2 wk	72	No	0%	0%	17% increase in short-term running performance; increases in O_2 deficit and muscle buffering capacity.
14	4,300 m	4 wk	38	Yes	n/a	+ 10%	$\dot{V}O_2$max increase not greater than that of control group.
15	3,100 m	17 d	66–68	Yes	0%	0%	Significant reductions in $\dot{V}O_2$max for some runners pre-to-postaltitude exposure; 220-m and 440-m run times reduced at altitude. Laboratory tests not predictive of track performances.
16	2,300 m	3 wk	73	Yes	0%	0%	3,218-m run times improved at altitude, but not pre-to-postaltitude exposure; altitude training was at 6.5% less absolute power output.
17	2,100 m	2 wk	74	Yes	n/a	0%	Increase in O_2 deficit.

Data sources: (1) Balke B, Nagle FJ, Daniels J. Altitude and maximal performance in work and sport activity. *JAMA.* 1965;194:646–649. (2) Klausen K, Robinson S, Micahel ED, Myhre LG. Effect of high altitude on maximal working capacity. *J Appl Physiol.* 1966;21:1191–1194. (3) Consolazio CF, Nelson RA, Matoush LO, Hansen JE. Energy metabolism at high altitude (3,475 m). *J Appl Physiol.* 1966;21:1732–1740. (4) Faulkner JA, Daniels JT, Balke B. Effects of training at moderate altitude on physical performance capacity. *J Appl Physiol.* 1967;23:85–89. (5) Maher JT, Jones LG, Hartley LH. Effects of high-altitude exposure on submaximal endurance capacity of men. *J Appl Physiol.* 1974;37:895–898. (6) Horstman D, Weiskopf R, Jackson RE. Work capacity during 3-week sojourn at 4,300 m: Effects of relative polycythemia. *J Appl Physiol.* 1980;49:311–318. (7) Buskirk ER, Kollias J, Akers RF, Prokop EK, Reategui P. Maximal performance at altitude and on return from altitude in conditioned runners. *J Appl Physiol.* 1967;23:259–266. (8) Pugh LGCE. Athletes at altitude. *J Physiol (Lond).* 1967;192:619–646. (9) Saltin B. Aerobic and anaerobic work capacity at an altitude of 2,250 meters. In: Goddard RF, ed. *The Effects of Altitude on Physical Performance.* Albuquerque, NM: The Athletic Institute; 1967: 97–102. (10) Faulkner JA, Kollias J, Favour CB, Buskirk ER, Balke B. Maximum aerobic capacity and running performance at altitude. *J Appl Physiol.* 1968;24:685–691. (11) Daniels J, Oldridge N. The effects of alternate exposure to altitude and sea level on world-class middle-distance runners. *Med Sci Sports.* 1970;2:107–112. (12) Dill DB, Adams WC. Maximal oxygen uptake at sea level and at 3,090-m altitude in high school champion runners. *J Appl Physiol.* 1971;30:854–859. (13) Mizuno M, Juel C, Bro Rasmussen T, et al. Limb skeletal muscle adaptation in athletes after training at altitude. *J Appl Physiol.* 1990;68:496–502. (14) Hansen JE, Vogel JA, Stelter GP, Consolazio CF. Oxygen uptake in man during exhaustive work at sea level and high altitude. *J Appl Physiol.* 1967;23:511–522. (15) Grover RF, Reeves JT. Exercise performance of athletes at sea level and 3,100 meters altitude. *Med Thorac.* 1966;23:129–143. (16) Adams WC, Bernauer EM, Dill DB, Bomar JB Jr. Effects of equivalent sea-level and altitude training on $\dot{V}O_2$max and running performance. *J Appl Physiol.* 1975;39:262–266. (17) Svedenhag J, Saltin B, Johansson C, Kaijser L. Aerobic and anaerobic exercise capacities of elite middle-distance runners after two weeks of training at moderate altitude. *Scan J Med Sci Sports.* 1991;1:205–214.

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TABLE 22-3

HYPOXIC EXERCISE WITH ALTITUDE ACCLIMATIZATION

Data Source	Training Altitude	Duration	Fitness (mL/kg/min)	Control Group?	$\dot{V}O_2$max Improvement		Comments
					at Altitude	on Return	
1	4,200 m	19 wk	45	No	+ 14%	+ 36%	Interval training in normoxia and hypoxia during alternating weeks. Endurance time to exhaustion increased > 100% in both normoxia and hypoxia.
2	3,050–4,268 m	3 wk	54	Yes	+ 10%	+ 10%	Because of small n, pre-to-postchange in normoxia and hypoxia $\dot{V}O_2$max not significantly different from controls (0% and 4%, respectively). Endurance performance improved for hypoxia training group in normoxia but not in hypoxia.
3	2,250 m	4 wk	46	Yes	+ 8%	+ 18%	Control group increased $\dot{V}O_2$max by 6% in normoxia, 4% at 2,250 m, and 0% at 3,450 m.
	3,450 m	4 wk	46	Yes	+ 14%	+ 10%	
4	2,500 m	5 wk	43	Yes	+ 12% to + 18%	+ 11% to + 15%	$\dot{V}O_2$max increases not greater than that of control group; endurance performance improvement specific to training altitude.
5	4,100–5,700 m	3 wk	56	Yes	+ 11	0%	Training for the control normoxic groups was at the same relative and absolute workloads as in hypoxia. No performance difference compared with controls. Training in hypoxia increased mitochondrial density, muscle fiber area, and capillary-to-fiber ratio.
6	2,300 m	4 wk	71	Yes	0%	0%	No $\dot{V}O_2$max increase for either group; work capacity increased more for the hypoxia-trained group, but only in hypoxia.

Data sources: (1) Bannister EW, Woo W. Effects of simulated altitude training on aerobic and anaerobic power. *Eur J Appl Physiol Med.* 1978;38:55–69. (2) Loeppky JA, Bynum WA. Effects of periodic exposure to hypobaria and exercise on physical work capacity. *J Sports Med Phys Fitness.* 1970;10:238–247. (3) Roskamm H, Landry F, Samek L, Schlager M, Weidemann H, Reindell H. Effects of a standardized ergometer training program at three different altitudes. *J Appl Physiol.* 1969;27:840–847. (4) Levine BD, Engfred K, Friedman DB, Kjaer M, Saltin B. High altitude endurance training: Effect on aerobic capacity and work performance. *Med Sci Sports Exerc.* 1990;22:S35. Abstract. (5) Desplanches D, Hoppeler H, Linossier MT, et al. Effects of training in normoxia and normobaric hypoxia on human muscle ultrastructure. *Pflugers Arch.* 1993;425:263–267. (6) Terrados N, Melichna J, Sylven C, Jansson E, Kaijser L. Effects of training at simulated altitude on performance and muscle metabolic capacity in competitive road cyclists. *Eur J Appl Physiol Med.* 1988;57:203–209.

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TABLE 22-4

ALTITUDE ACCLIMATIZATION WITH NORMOXIC EXERCISE

Data Source	Training Altitude	Duration	Fitness (mL/kg/min)	Control Group?	$\dot{V}O_2$max Improvement at Lower Altitude	Comments
1	1,300 m	4 wk	65	Yes	5%	Experimental and control groups trained together at 1,300 m, but the experimental group lived at 2,500 m ("living high, training low"). Blood volume increased 500 mL and 5-km run time decreased 30 sec in experimental group. No changes in $\dot{V}O_2$max, blood volume, or run time for control group.

Data source: (1) Levine BD, Stray-Gundersen J, Duhaime G, Snell PG, Friedman DB. "Living High—Training Low": The effect of altitude acclimatization/normoxic training in trained runners. *Med Sci Sports Exerc.* 1991;23:S25. Abstract.

TABLE 22-5

NORMOXIC AND HYPOXIC EXERCISE AFTER ALTITUDE ACCLIMATIZATION

Data Source	Training Altitude	Breathing	Duration	Fitness (mL/kg/min)	Work Load	$\dot{V}O_2$max Improvement		Comments
						in Hypoxia	in Normoxia	
1	3,600 m	Ambient[‡]	6 wk	42	Control	15%	14%	Training for the two experimental groups was at the same relative or absolute work load as the control hypoxia group, but while training, the experimental groups breathed only high concentrations of O_2 gas (eg, "living high, training low").
	0 m[†]	0.314%			Same relative	17%	20%	
	0 m[†]	0.314%			Same absolute	8%	10%	

[*] Control hypoxia group: altitude natives breathing ambient altitude air

[†] Experimental group

[‡] O_2 content of ambient air: 0.2093%

Data source: (1) Levine BD, Stray-Gundersen J, Duhaime G, Snell PG, Friedman DB. "Living High—Training Low": The effect of altitude acclimatization/normoxic training in trained runners. *Med Sci Sports Exerc.* 1991;23:S25.

Adapted with permission from Fulco CS, Rock PB, Cymerman A. Improving athletic performance: Is altitude residence or altitude training helpful? *Aviat Space Environ Med.* 2000;71(2):168.

only. It is interesting that most studies of this design report results that are consistent with an additive or potentiating role of hypoxic exercise training for subsequent hypoxic or normoxic performance evaluations.[56,128–131]

Why living at sea level and training at altitude may be more beneficial for improving exercise performance than both living and training at altitude is not well understood. Possible differences in success rates between these two experimental approaches do not seem to be related to differences in absolute exercise intensity, training altitude, training program duration, subject fitness levels, and peripheral muscle changes. The only consistent differences are increases in hematocrit and hemoglobin in subjects who both trained and resided at altitude, compared with studies in which subjects trained in hypoxia but lived at sea level. Of course, during a typical 2- to 5-week period of living and training at altitude (a typical length of time for most of these studies), increases in hematocrit and hemoglobin concentrations primarily reflect hemoconcentration that, as was mentioned above, is due to decreases in plasma and blood volume—changes that may attenuate the effects of hypoxia per se[43,75] but may not provide an additional benefit for altitude or sea-level physical performance.

When results of the physiological and exercise performance changes of the two experimental approaches are compared, the data suggest that, for both sea-level and altitude exercise performance, training but not living under hypoxic conditions may be more beneficial than training and living at altitude, and that the benefit may be related to a maintained blood volume. It is unfortunate that studies in which subjects live at sea level and train under hypoxic conditions have not typically reported timed track trials and other athletic-event evaluations. Doing so would likely allow a more accurate appraisal of the potential benefits of training, but not living, in hypoxia. Thus, the limited data from studies using widely differing experimental designs preclude forming firm conclusions regarding the efficacy of periodic hypoxic training for subsequent sea-level exercise performance.

Normoxic Exercise Training During Altitude Acclimatization

It is documented that inability to maintain exercise intensity during exercise training at sea level can result in a decline in $\dot{V}O_2max$.[111] It is possible, therefore, that the necessary reduction in exercise intensity while training at altitude may lead to "relative deconditioning" and offset potential beneficial changes resulting from altitude acclimatization.[26] Living at altitude but training at a lower altitude ("living high and training low") theoretically allows both the advantageous changes of acclimatization to develop and the opportunity to train without reducing exercise intensity.

Using this approach, Levine and colleagues[133] trained nine highly conditioned runners ($\dot{V}O_2max$ [sea level] = 64.9 mL/kg/min) for 4 weeks at 1,300 m. All subjects trained together at the same exercise intensity. Three of the subjects lived at 1,300 m (the "sea-level" group) and six lived at 2,500 m (the "altitude" group). Before training, there were no differences between groups in $\dot{V}O_2max$, 5-km run time, or blood volume. For the sea-level group, there were no significant changes in any of the measures after training. For the altitude group, however, both $\dot{V}O_2max$ and blood volume increased and the time to run 5 km decreased (Table 22-4). The investigators concluded that altitude acclimatization with sea-level training improved exercise performance at sea level.

Because of these findings, Levine and Stray-Gundersen[36] and Levine, Roach, and Houston[37] hypothesized 1 year later that altitude acclimatization rather than hypoxic exercise per se was the key to altitude training because the natural form of "blood doping" (increased blood volume and hemoglobin) enhanced oxygen transport. In contrast, as discussed above, hypoxic exercise training has been reported to increase $\dot{V}O_2max$ without inducing changes in hemoglobin concentration or blood volume.[56,133] Perhaps hypoxic exercise training increases the "training effect," as evidenced by greater increase in aerobic enzyme activities and other peripheral changes.[108,129,130] Additional studies with the experimental design of "living high and training low" are still needed to confirm or refute these results.

Normoxic and Hypoxic Exercise Training After Altitude Acclimatization

The studies reviewed above were conducted using sea-level residents who lived or trained, or both, under hypoxic conditions. Some[19,24,25,47,56,128,131,133,134] reported that hypoxic exercise training enhances maximal performance compared to normoxic training on return to sea level, while others[27–30,45,52,107,126,129,130,132] report no such enhancement. The discrepancies have been ascribed to[135]

1. differences in the level and duration of altitude exposure
2. differences in the degree of prealtitude exposure fitness levels,
3. differences in the interindividual rate of early altitude acclimatization, and
4. variable intensity training programs between or within studies.

Some altitude exercise training studies were conducted during the early altitude exposure period and ended long before altitude acclimatization was complete. Other altitude exercise training studies were accomplished during repeated acute hypoxic exposures where some indices of acclimatization were purposefully avoided. Having individuals train at altitude after "complete" acclimatization should both minimize the confounding variability due to changes associated with altitude acclimatization and allow assessment of hypoxic exercise training only.

To test this hypothesis, Favier and colleagues[135] trained 30 native-born, high-altitude residents, (sea-level $\dot{V}O_2$max ~ 42 mL/kg/min), at 3,600 m on a cycle ergometer 30 min/d, five times per week, for 6 weeks (Table 22-5). Subjects were randomly assigned to one of three groups of ten. One group trained at altitude at 70% of $\dot{V}O_2$max breathing ambient air (the control group). The other two groups trained at altitude but inhaled a normoxic gas mixture (FIO_2 = 0.314 at 500 mmHg, sea-level equivalent) and exercised at the same relative work load (70% of normoxic $\dot{V}O_2$max) or at the same absolute work load (70% of hypoxic $\dot{V}O_2$max) as the control group. The normoxic training groups were, in essence, living at high altitude and training at low. As the fitness levels of the subjects improved, the work loads were increased to maintain exercise intensities at the desired levels. All three groups demonstrated an improvement in $\dot{V}O_2$max in response to training (the magnitude of which was similar to that of the same conditioning program used for an earlier sea-level training study conducted by the research team).[136] The results suggest that the documented increase in hemoglobin concentration induced by altitude acclimatization does not provide additional benefits in terms of increasing $\dot{V}O_2$max with training. The results also indicate that the combination of altitude acclimatization and oxygen supplementation during exercise training (to allow training at an increased power output and training intensity) does not produce an increase in $\dot{V}O_2$max greater than training in hypoxia. These results do not support the belief that the potential beneficial effect of hypoxia is lessened by the inability to exercise at a high intensity at altitude.[28,37,42] The reason or reasons for the diverging results and conclusions of this study[135] and those of Levine and colleagues[133] are not readily apparent. More studies with these experimental approaches are warranted.

SUMMARY

The ability to perform muscular exercise is usually evaluated by measuring maximal aerobic power ($\dot{V}O_2$max) during increasingly severe exercise that leads to exhaustion within minutes. In ascending to altitude, an individual is exposed to a progressive decrease in atmospheric pressure that is associated with reductions in inspired, alveolar, and arterial oxygen pressures. As a consequence, $\dot{V}O_2$max also declines. A comprehensive review of the literature indicates that the minimal elevation at which a decrease in $\dot{V}O_2$max is detectable is approximately 580 m. It is possible that the minimal altitude is even lower, especially for highly conditioned individuals. Sixteen experimental and physiological factors have been implicated in the wide variation in percentage $\dot{V}O_2$max decrement at altitudes from 580 m to 6,000 m. Fitness level, preexposure elevation, gender, and duration of exposure were all qualitatively assessed to determine their contribution to the overall variability. Of these, fitness-level differences caused the most variability and gender differences contributed the least.

Submaximal oxygen uptake is similar for a given activity at sea level and at altitude. But because $\dot{V}O_2$max declines, the relative exercise intensity is increased and therefore submaximal exercise performance is adversely affected. To maintain the same level of perceived difficulty at altitude for training or working on civilian or military tasks, the exercise or work loads must necessarily be reduced. Long-duration activities will be impaired more than shorter-duration activities at a given altitude. Muscle strength, maximal muscle power, and, likely, anaerobic performance are not affected at altitude as long as muscle mass is maintained. Physical performance may be improved at altitude compared with sea level in activities that have a minimal aerobic component and can be performed at high velocity (eg, sprinting).

Altitude acclimatization is associated with a multitude of ventilatory, hematological, and metabolic adaptations that have been thought to induce a beneficial effect on exercise performance. Training or living, or both, at altitude can improve altitude exercise performance in athletic events or military activities lasting longer than about 2 minutes. In contrast, findings based on controlled studies do not support a beneficial effect of altitude training on subsequent sea-level performance. Any potential benefit induced by altitude acclimatization for subsequent sea-level performance may be offset by the inability to maintain exercise intensity. Living at altitude but training at a lower altitude permits the theoretical advantage of both acclimatization and training without reducing exercise intensity. This paradigm appears promising but is still open to question, since native-born, high-altitude residents who trained at altitude with oxygen supplementation (in essence, living high but training low) did not improve $\dot{V}O_2$max more than native-born, high-altitude residents who trained at altitude without supplementation. More research is clearly warranted to determine the most advantageous strategy, if any, for improving sea-level exercise performance.

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Chapter 22: ATTACHMENT

DATA SOURCES FOR GRAPHS IN CHAPTER 22

Fig. 22-1. Civilian and military investigations: (1) Cymerman A, Pandolf KB, Young AJ, Maher JT. Energy expenditure during load carriage at high altitude. *J Appl Physiol.* 1981;51:14–18. (2) Faulkner JA, Daniels JT, Balke B. Effects of training at moderate altitude on physical performance capacity. *J Appl Physiol.* 1967;23:85–89. (3) Dill DB, Adams WC. Maximal oxygen uptake at sea level and at 3,090-m altitude in high school champion runners. *J Appl Physiol.* 1971;30:854–859. (4) Klausen K, Robinson S, Micahel ED, Myhre LG. Effect of high altitude on maximal working capacity. *J Appl Physiol.* 1966;21:1191–1194. (5) Buskirk ER, Kollias J, Akers RF, Prokop EK, Reategui P. Maximal performance at altitude and on return from altitude in conditioned runners. *J Appl Physiol.* 1967;23:259–266. (6) Faulkner JA, Kollias J, Favour CB, Buskirk ER, Balke B. Maximum aerobic capacity and running performance at altitude. *J Appl Physiol.* 1968;24:685–691. (7) Grover RF, Reeves JT. 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