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Altitude Preexposure Recommendations for Inducing Acclimatization

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Abstract

Muza, Stephen R., Beth A. Beidleman, and Charles S Fuco. Altitude preexposure recommendations for inducing acclimatization. *High Alt. Med.Biol.* 11:87–92, 2010.—For many low-altitude (<1500 m) residents, their travel itineraries may cause them to ascend rapidly to high (>2400 m) altitudes without having the time to develop an adequate degree of altitude acclimatization. Prior to departing on these trips, low-altitude residents can induce some degree of altitude acclimatization by ascending to moderate (>1500 m) or high altitudes during either continuous or intermittent altitude preexposures. Generally, the degree of altitude acclimatization developed is proportional to the altitude attained and the duration of exposure. The available evidence suggests that continuous residence at 2200 m or higher for 1 to 2 days or daily 1.5- to 4-h exposures to >4000 m induce ventilatory acclimatization. Six days at 2200 m substantially decreases acute mountain sickness (AMS) and improves work performance after rapid ascent to 4300 m. There is evidence that 5 or more days above 3000 m within the last 2 months will significantly decrease AMS during a subsequent rapid ascent to 4500 m. Exercise training during the altitude preexposures may augment improvement in physical performance. The persistence of altitude acclimatization after return to low altitude appears to be proportional to the degree of acclimatization developed. The subsequent ascent to high altitude should be scheduled as soon as possible after the last altitude preexposure.

Key Words: altitude acclimatization; acute mountain sickness; high altitude

Introduction

Lowland (<1500 m) residents rapidly ascending to high (>2400 m) and especially very high (>3500 m) or extreme (>5500 m) altitudes are at risk of developing high altitude illness (Gallagher and Hackett, 2004) and experiencing substantial impairment of their physical and cognitive work performance (Fulco et al., 1998). Altitude acclimatization is a series of physiological adjustments that compensates for the reduction in ambient oxygen. Altitude acclimatization is the best strategy for the prevention of acute mountain sickness (AMS) (Forgey, 2006) and allows people to achieve the maximum physical and cognitive work performancs possible for the altitude to which they are acclimatized (Fulco et al., 2000; Banderet et al., 2002). A gradual or staged ascent with a first-night sleeping altitude of no more than 2400 m and daily altitude gain limited to 300 to 600 m is the recommended strategy for induction of altitude acclimatization (Forgey, 2006). However, for many climbers and trekkers on a tight schedule, there may be insufficient time to develop an adequate degree of

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altitude acclimatization. For example, an ascent of Mt. Kilimanjaro (5896 m) following the fastest recommended graded ascent rate of 600 m/day above 2500 m (Hackett and Roach, 2001) would require 8 days (6 climbing days and 2 rest days) for acclimatization. By comparison, on a popular commercial climbing route to the summit, the relatively fast ascent includes only 4 or 5 sleep nights above 2500 m. Individuals following this relatively rapid ascent experience a high incidence (~75%) of acute mountain sickness and only 51% to 61% successfully reach the summit (Karinen et al., 2008; Kayser et al., 2008, Davies et al., 2009). Acclimatization to altitude prior to starting this ascent would likely decrease susceptibility to AMS, improve physical performance, and increase summiting success.

Altitude acclimatization is most commonly induced by continuous exposure to altitudes >1500 m. However, for persons living at low altitude, in the months to weeks prior to departing on a climbing trip, continuous residence at high altitude may not be possible. For some low-altitude residents, an occasional 1- or 2-day trip to moderate or higher altitude may be possible. The question is whether this type of altitude preexposure provides any benefit and, if so, how long does the benefit persist.

In lieu of acclimatization, several medications are available that effectively decrease susceptibility to altitude illness (Hackett and Roach, 2001). However, all these medications (e.g., acetazolamide, dexamethasone, and sildenafil) have potential adverse effects that limit their use, and none of these pharmaceutical interventions directly improves physical work performance. In fact, at the highest recommended dosage, acetazolamide decreases endurance performance (Stager et al., 1990, Garske et al., 2003), thus exacerbating altitude-induced work impairment. Conversely, lower dosages of acetazolamide may not effectively prevent AMS at altitudes >4000 m (Dumont et al., 2000). Thus, altitude acclimatization remains the best approach to negating the detrimental effects of altitude on health and human performance.

The purpose of this review is to provide a brief description of the key physiological adaptations of altitude acclimatization, to assess the benefit of altitude preexposure, and to provide recommendations for planning and timing altitude preexposure prior to departing on a sojourn to high altitudes. Because of possible differences between hypobaric and normobaric hypoxia and limitations on the length of this review, only the use of hypobaric exposures to real or simulated altitude for inducing altitude acclimatization is reviewed.

Altitude Acclimatization

There are many excellent, comprehensive reviews of altitude acclimatization (Bisgard and Forster, 1996; Ward et al., 2000, Young and Reeves, 2002). This review we will focus on the key adaptations that occur over the first few hours to days of altitude exposure.

Available evidence suggests that in the altitude range of from 900 to 1500 m a degree of hypobaric hypoxia is reached that stimulates development of altitude acclimatization (Kellogg 1968, Honigman et al., 1993, Reeves et al., 1993). Two key adaptations comprising altitude acclimatization are increased ventilation and decreased total body water, resulting in a reduced plasma volume (i.e., hemoconcentration). Ventilatory acclimatization to altitude is characterized by progressive increases in ventilation, arterial oxygen partial pressure, and oxygen saturation (Sao_2) and a drop of arterial carbon dioxide partial pressure along with normalization of arterial pH during the first 5 to 9 days of residence at high altitude (Bisgard and Forster, 1996). Concomitant with the increase in ventilation, the oxygen-carrying capacity of the blood is increased by hemoconcentration resulting from reduction in plasma volume (Hoyt and Honig, 1996). The net result of the increased ventilation and hemoconcentration is a near normalization of arterial oxygen content after an approximately 7-day residence at high altitude (Sawka et al., 2000). Ventilatory acclimatization can be accelerated by the drug acetazolamide (Kronenberg and Cain, 1968).

Acute exposure to high altitude increases heart rate and cardiac output to maintain systemic oxygen delivery (Mazzeo et al., 1994). As arterial oxygen content increases with altitude acclimatization, both cardiac output and peripheral blood flow return toward normal. This decrease in blood flow may contribute to improved exercise tolerance by reducing cardiac work and allowing more diffusion time for tissue extraction of oxygen (Sawka et al., 2000). Acute exposure to high altitude causes hypoxic pulmonary vasoconstriction, resulting in increased pulmonary arterial pressure that can, in a few individuals, bring about high altitude pulmonary edema (HAPE) (Gallagher and Hackett, 2004). Recently, we have shown that staging at ~2200 m for 6 days significantly attenuated the pulmonary arterial pressure (PAP) increase during subsequent direct ascent to 4300 m (Baggish et al., 2010), which may reduce the risk of developing HAPE. With acclimatization, there is increased transport and oxidation of carbohydrates within metabolically active tissues (Brooks et al., 1991). Thus, in a low-oxygen environment, carbohydrates are the preferred fuel source (Fulco et al., 2005).

With continuous altitude residence, the physiological strain of exercise is lessened, and exercise tolerance at altitude is improved compared to that initially on arrival (Horstman et al., 1980; Fulco et al., 2005). Moreover, the symptoms of AMS abate with acclimatization (Gallagher and Hackett, 2004). For example, if individuals afflicted with AMS stop further ascent and rest at their current altitude, for ~80% the AMS symptoms resolve over 2 to 7 days (Gallagher and Hackett, 2004) as acclimatization to hypoxia is achieved. These outcomes reduce the risk by improving judgment, decreasing fatigue and illness, and increasing the likelihood of successfully completing a trek or ascent at high altitude.

Acclimatization is elevation specific; that is, full acclimatization at one altitude confers only partial acclimatization to a higher altitude. The amount of time required for a person to become acclimatized is a function of that individual's physiology and the magnitude of the hypoxic challenge, as defined by the altitude attained (Reeves et al., 1993). Individuals with no recent (>1 month) altitude acclimatization require the greatest physiological compensations and thus the longest time to acclimatize. Individuals residing at moderate or high altitudes will achieve acclimatization to a higher altitude more rapidly (Muza et al., 2004). For most people exposed to high altitudes, 70% to 80% of the respiratory component of acclimatization occurs in 4 to 10 days, and 80% to 90% of their overall acclimatization is accomplished by 2 weeks to a month (Purkayastha et al., 1995). The time course for several acclimatization outcomes (physical and cognitive performances, AMS, Sao_2, and heart rate) measured in our Pikes Peak Laboratory at 4300 m are illustrated in Fig. 1.

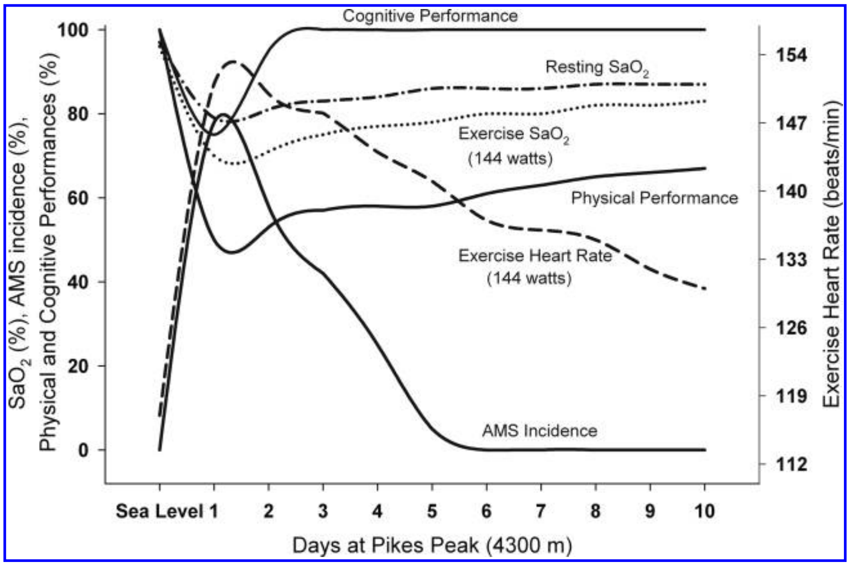

FIG. 1. Representative time course for altitude acclimatization of low altitude residents directly ascending to 4300 m.

Altitude Deacclimatization

Once acquired, acclimatization is maintained as long as the individual remains at altitude, but it is lost over a few days to weeks after return to lower elevations. The rate at which altitude deacclimatization occurs has not been well-studied. Our laboratory (Lyons et al., 1995; Muza et al., 1995; Beidleman et al., 1997) acclimatized lowland residents at 4300 m for 16 days and then returned them to sea level for 7 days. On day 8 at sea level, they ascended to 4300 m for an overnight exposure in our hypobaric chamber. These previously acclimatized subjects retained about 50% of their ventilatory acclimatization, were completely absent of AMS, and had lessened physiological strain during submaximal exercise. Savourey and colleagues (1996) reported on a group of climbers returning to low altitude 10 days after leaving Mt. Everest base camp; when reexposed to 4500 m in a hypobaric chamber, resting, and exercise Sao_2 were still significantly higher than prior to acclimatization. Finally, Sato and colleagues (1992) measured the hypoxic ventilatory response (HVR) in lowland residents over 5 days residing at 3810 m and over 1 week upon return to sea level. The HVR was significantly elevated by day 3 at altitude and remained elevated over the first 3 days back at sea level. However, contrary to the results of these studies, Richalet and colleagues (2002) observed no decrease in AMS severity during the first 2 days at very high altitude in miners alternating between working 7 days at 3800 to 4600 m and resting 7 days at sea level. Because this was a field study, other environmental or work-related factors may have negated any beneficial acclimatization effect in these miners. Overall, the majority of the findings from these direct studies of altitude deacclimatization suggest that acclimatization diminishes after descent to low altitude, but is retained for at least 1 week in well-acclimatized individuals and for at least 3 days in individuals with less well developed acclimatization.

One study provides indirect evidence that functionally useful acclimatization persists for days to weeks. Schneider and colleagues (2002) assessed AMS in climbers arriving at the Capanna Margherita (4559 m) and examined several established risk factors for AMS. They found that the three independent determinates of susceptibility to AMS were prior history, rate of ascent, and altitude preexposure. Sufficient altitude preexposure was determined to be 5 or more days spent above 3000 m in the preceding 2 months. Independently of known susceptibility, both adequate altitude preexposure and slow ascent reduced AMS prevalence by ~50%. Unfortunately, the investigators did not determine the altitude exposure profiles or the timing of the preexposure relative to the actual ascent and assessment of AMS. Finally, it is possible that individuals with a history of AMS ceased climbing to high altitude and thus, through self-selection, the climbing population in this study did not include individuals with high susceptibility to AMS. In summary, although significant data gaps still exist, the preponderance of evidence suggests that altitude acclimatization persists for days to several weeks after the last preexposure.

Preexposure Altitude Acclimatization

There are two approaches to preexposure altitude acclimatization: continuous and intermittent altitude exposures. There is ample evidence that continuous residence at moderate and higher altitudes induces acclimatization (Houston, 1955; Hansen et al., 1967; Houston and Dickinson, 1975; Evans et al., 1976; Hackett et al., 1976; Stamper et al., 1980; Purkayastha et al., 1995; Beidleman et al., 2009; Fulco et al., 2009; Baggish et al., 2010). However, in all these prior studies, further ascent to higher altitude immediately followed the staging or graded ascent to higher altitudes. As previously described, lowlanders well acclimatized to 4300 m who returned to low altitude for 7 days retained beneficial acclimatization upon reascent to 4300 m on day 8 (Lyons et al., 1995; Muza et al., 1995; Beidleman et al., 1997). There are no published reports of the duration of beneficial acclimatization for other combinations of high altitude and exposure durations.

Altitude acclimatization can be induced by discontinuous or intermittent altitude exposure (Muza, 2007). There is ample evidence that intermittent altitude exposures do induce ventilatory acclimatization (Nagasaka and Satake, 1969; Savourey et al., 1996; Chapman et al., 1998; Katayama et al., 1998; Rodriguez et al., 2000; Ricart et al., 2000; Katayama et al., 2001;

Beidleman et al., 2004) and improve work performance (Roskamm et al., 1969; Terrados et al., 1988; Vallier et al., 1996; Beidleman et al., 2003; Beidleman et al., 2008). Only one study (Beidleman et al., 2004) has examined AMS following intermittent altitude exposures. We found that AMS was absent at 4300 m immediately following 15 days of 4-h daily exposure to 4300 m. Including exercise training at high altitude may (Roskamm et al., 1969) or may not (Beidleman et al., 2003) augment improvement in exercise performance at high altitude. In the majority of these studies, the assessment of "beneficial" acclimatization was made within 24 h of the last preexposure. Hence, the persistence of these beneficial adaptations is unknown. Moreover, most of these studies used hypobaric chambers, and the exposures were to very high altitudes (>4000 m) that cannot be easily attained in the natural environment by individuals residing at low altitude. There are no published studies of the efficacy of a more likely altitude preexposure scenario employing weekend sojourns to high altitude repeated over 2 or more weeks. For example, at the relatively easily attainable altitude of 2200 m, within the first 2 days (i.e., a weekend) significant ventilatory acclimatization develops (Beidleman et al., 2009). However, how long this degree of acclimatization will persist after descent is unknown.

Finally, as previously described, Schneider and colleagues (2002) found that sufficient altitude preexposure was 5 or more days spent above 3000 m in the preceding 2 months. However, because the timing of the altitude preexposure relative to the actual ascent and assessment of AMS was not assessed, it is possible that these preexposures occurred closer to the actual climb than implied by the 2-month preexposure period.

Recommendations

Given the limited data, it is difficult to provide definitive recommendations for developing efficacious altitude acclimatization using preexposure (continuous or intermittent) protocols. Additionally, the planned rate of ascent and ultimate elevation of the subsequent trip will dictate what degree of altitude acclimatization one should attempt to achieve prior to departing for the ascent. For example, individuals planning rapid ascents to extreme altitudes, such as Mt. Kilimanjaro (5896 m), would require more acclimatization than individuals planning a trek along the Pacific Crest trail where the peak elevation is 4009 m. Thus, the following guidelines should be viewed as tentative and employed as broad rather than specific guidance.

Individuals residing within or above 900 to 1500 m have likely developed a degree of acclimatization proportional to the magnitude of the hypoxic stimulus. Thus, upon ascent to higher altitudes they will likely experience a proportional reduction in susceptibility to developing AMS and also mitigate the hypoxic-induced decrement in physical work performance. For individuals residing below 900 to 1500 m, some degree of altitude acclimatization will be induced by frequent exposures to high altitude in the weeks prior to departing on a trip to high altitudes. It is well established that some degree of ventilatory acclimatization will be developed over 1 to 2 days of continuous residence at moderate (>1500 m) or high (>2400 m) altitudes and with daily 1.5- to 4-h exposures to >4000 m. There is evidence that 5 or more days above 3000 m within the last 2 months prior to an ascent to high altitude will significantly decrease AMS. Generally, the degree of the altitude acclimatization developed is proportional to the altitude attained and the duration of exposure. The greater the magnitude of altitude acclimatization, the longer functionally useful acclimatization will persist upon descent. However, in the absence of definitive evidence, ascent to high altitude should be scheduled as soon as possible after the last altitude preexposure.

Disclosures

The authors have no conflicts of interest or financial ties to report. Approved for public release; distribution is unlimited. The views, opinions, and/or findings contained in this publication are those of the authors and should not be construed as an official Department of the Army position, policy, or decision unless so designated by other documentation. Any citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement or approval of the products or services of the organizations.

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