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for CECS Level II Coaches

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SPECIFIC THEME: Training at altitude

GENERAL THEME: Altitude effects and adaptations

Specific Theme

TRAINING AT ALTITUDE

1 History of altitude training

Mountaineers, aviators, and laborers who were hired to perform heavy work at above 3000 m height were the first who were concerned about the effects of altitude on human work and performance. These early concerns over altitude were simply related to performing physical tasks, most of which were non-competitive in nature (cf. Daniels, 1990, p. 14).

The problems of altitude training were dealt with for the first time in Bulgaria in 1953 (cf. Popov, 1994, p. 17). Also in the 1950s, Soviet speed skaters were submitted to systematic altitude training in order to improve their performance (cf. Hollmann, 1994, p. 8). However, it was not before 1963 that the problems of competing at altitude became the focus of great interest amongst sports physiologists. In that year the International Olympic Committee decided to hold the 1968 Olympic Games in Mexico City.

Clearly, athletes who were to compete at Mexico City's 2,240 m altitude would require considerably longer to acclimatize than the period normally associated with the interval between arrival at the Olympic venue, and commencement of competition (cf. Daniels, 1990, p. 14; Dick, 1979, p. 11).

In 1965, experiments conducted as a preparation for this "altitude Olympics" led to the first description of the possibility of carrying out hypoxia training in a laboratory. These experiments as well as those during a several-weeks stay in Mexico City one year before the Olympic Games were conducted by the German sports physician Reindell and by his Swedish colleague Saltin. In this way, previous estimations and assumptions about acute altitude reactions and chronic adaptations in connection with moderate physical work could be corroborated and further knowledge could be obtained (cf. Hollmann, 1994, p. 8).

To assist in altitude acclimatization, many countries arranged for their athletes to train at an altitude equal to or higher than that of Mexico City.

This led to the introduction of the new expression *altitude training* to the coaches' vocabulary (cf. Dick, 1979, p. 11).

All things considered, it can be said that there has presumably never been, in the history of altitude research, such an intensive advance of knowledge about human performance behavior at medium altitudes as during the 1960s, in connection with the 1968 Olympics in Mexico City (cf. Hollmann, 1994, p. 8).

The Mexico City experiences then made it painfully clear how altitude affected performances in longer endurance events. If the performance times in the endurance running events at the 1968 Mexico City Olympics are compared with the sea-level best times those same athletes achieved earlier that year, it can easily be seen that their altitude performances were consistently slower, even though there is no doubt that they were supremely fit at the Games. Virtually every medallist, from the 1,500 m to the marathon, was either an altitude native or had trained extensively at altitude before competing in Mexico City (cf. Bueno, 1998, p. 10; Martin, 1994, p. 51).

Whereas the first applications of altitude training had been to prepare athletes for competition at altitude, the nature of the physiological adjustments associated with acclimatization introduced the concept of capitalizing on such adjustments in pursuit of competitive advantage at sea level. These adjustments are clearly connected with the oxygen transporting system, and consequently, athletes seeking increased efficiency of this

system for competitive advantage in their particular discipline were encouraged to pursue this type of training. Perhaps, also, the success of endurance athletes living and training at altitude from Kenya and Ethiopia encouraged the sports world to accept the logic of altitude training for sea-level competition (cf. Bueno, 1998, p. 10; Dick, 1979, pp. 11-12).

As a result, in the post-Mexico pre-Munich years, many countries invested considerable capital on the one hand to advantage their athletes, and on the other to attempt to produce a sound scientific basis to this area of training theory via research (cf. Dick, 1979, p. 12).

2 How high should an athlete live and train?

Acclimatization to altitude depends on oxygen delivery to peripheral tissues, which decreases linearly with oxyhemoglobin saturation. Thus red cell mass does not appear to increase until oxygen's partial pressure (PO_2) decreases below approximately 65 mmHg, when saturation begins to fall. For most individuals, this threshold altitude is somewhere between 2,200 and 2,500 m, although some small changes have been reported in endurance athletes at altitudes as low as 1,250 m. Above 2,500 m such adaptations are likely to be greater with increasing altitude unless acute mountain sickness intervenes or marked hypoxia (above 4,000 m) results in a catabolic state characterized by weight loss with reduction in muscle mass. An altitude of 2,500-2,800 m thus appears to maximize acclimatization and minimize compli-

cations (cf. Levine & Stray-Gundersen, 1999, p. 95). In practice, altitude training is normally conducted at so-called medium or moderate altitudes between 1,800 and 2,400 m. Long-distance coach Bruce Tulloh (cf. Alford, 1994, p. 39) states that his athletes generally get up to 2,150 m and do the upper runs on the slopes and that they do never go below 1,850 m. The altitude training center at Font Romeu (France) is exactly 1,850 m high. Other altitude training centers around the world are: St. Moritz (Switzerland), Sestriere (Italy), Belmeken (Bulgaria), Flagstaff (Arizona/USA), Gunnison, Alamosa and Boulder (Colorado/USA). During the winter months, Nairobi (Kenya), Addis Ababa (Ethiopia), South Africa, and Mexico City are popular alternatives for altitude training camps (cf. Baumann et al., 1994, pp. 24-25; Popov, 1994, p. 17).

According to Levine & Stray-Gundersen (1999, p. 95) high-intensity, interval workouts should be conducted as close to sea level as possible, preferably below 1,500 m, to maximize running speed and training intensity.

However, in some cases, additional factors deserve consideration when choosing training altitude. Martin (1994, p. 54) points out that depending upon the place of normal residence, one particular altitude may or may not seem stressful. As an example, athletes native to Mexico City do not consider their 2,300 m as altitude. Instead, they find it appropriate to go to 3,500 m, in the mountainous hills around Toluca, for an altitude stimulus. Athletes living along the seacoast, however, find the altitude of

Mexico City quite challenging. Almost all elite athletes who reside at sea level find living and/or prolonged training above 2,700 m too stressful for any predictable and consistent benefits. The combination of skeletal muscle wasting, slowness of tolerable training pace and ongoing tendency towards dehydration more than negates any benefits of additional oxygen transport ability, caused by the adaptive increase in red cell mass.

3 Goals and timing of altitude training

The main objective of an altitude training camp is to develop a strong aerobic base. Therefore, the most effective time for an altitude training camp is always the first period of basic preparation after competition (i. e. March or April, after indoor competition or cross country, and July, after the first block of track competitions) (cf. Baumann et al., 1994, p. 23). Another reason for this timing is that middle distance runners, for example, find it difficult to maintain and/or improve their 'turnover' (leg speed, quickness) at altitude (cf. Martin, 1994, p. 54). An altitude training camp should only be planned if there is enough time available for a 3-week stay, plus 12-14 days re-acclimatization to sea level (cf. Baumann et al., 1994, p. 23).

4 Special considerations that need to be addressed before training at altitude

Iron stores play a critical role in the ability to respond to altitude training. In a series of studies involving more

than 100 competitive distance runners training at altitude, 40% (60% of women and 25% of men) were found to have reduced iron stores based on a low serum ferritin level. The athletes with low ferritin levels prior to altitude exposure (male and female) were unable to increase the volume of red blood cell mass (blood volume minus plasma volume) and did not increase VO_{2max} or improve running performance. Because iron is a critical component of myoglobin as well as mitochondrial cytochromes, iron deficiency may not only compromise oxygen-carrying capacity but also inhibit oxygen extraction (arteriovenous O_2 difference) and reduce VO_{2max} and performance, even in non-anemic athletes. Thus iron stores must be normalized before undertaking a period of altitude training. Normalization may require high doses of oral iron (up to 500 mg elemental iron/day) in divided doses, which are usually best tolerated in liquid, pediatric preparation (Feosol, 5-20 ml, 1-3 times/day, taken with vitamin C, 30 minutes before or 60 minutes after a meal) (cf. Levine & Stray-Gundersen, 1999, p. 95).

5 Duration, frequency, and methodology of a high altitude training camp

5.1 Duration and frequency

An altitude training camp at medium height usually lasts three weeks, long enough to record individual characteristics. Experience has shown that repeated stays at altitude (two or three times a year) have a larger effect on the endurance performance capacity than a single altitude training

camp and facilitates as well as shortens acclimatization and re-acclimatization (cf. Bueno, 1998, p. 13).

The aim of the first training camp at the beginning of the season is to improve basic conditioning and aerobic metabolism. The training conducted during the second stay at altitude depends on periodization. Athletes who have competed in indoor races must allow for a short recovery time before departing to altitude. Those who did not take part in winter competitions adjust their second altitude camp to specific preparation on performance capacity according to the beginning of the first competition block.

Athletes who have the time and possibility to take part in a third altitude training camp should time it to correspond to the main competitions of the year between June and August. This requires a break in competitions of 5-6 weeks, 3-4 weeks for altitude training and 2-3 weeks for re-acclimatization prior to the most important competition. The training program should be most specific and contain all race preparation elements (cf. Bueno, 1998, p. 13; Popov, 1994, pp. 18-19).

5.2 Training methodology

The proportion between volume and intensity at altitude depends on the aim of the involved training period (preparation or competition period). The planning of training must constantly take into consideration the effects of hypoxia on training loads. These effects can be determined from heart rate measurements and lactate levels. Even if running speeds are below those at sea level, it is advis-

able to maintain sea-level heart rates (cf. Bueno, 1998, p. 13).

Due to hypoxia-created limited VO_{2max} , reduced alkaline reserves and reduced buffering capacity of blood, lactate is at altitude considerably higher than for an equal load at sea level. For this reason neither high volume/high intensity, nor high lactate tolerance sessions should be attempted at altitude (cf. Dick, 1992, p. S205).

Altitude training at 2,200 m, in comparison to training at sea level, can be responsible for a 10% higher load on the organism. This means that an endurance load of 4 m/sec (14.4 km/h) at altitude corresponds to a load of 4.4 m/sec (15.8 km/h) at sea level (cf. Bueno, 1998, p. 14).

Training methods to develop basic and medium duration endurance (endurance runs and interval method) do not differ at altitude from the methods employed at sea level. Even the volume and number of repetitions can be identical. However, running speed must be lowered and recoveries lengthened. Load increases (higher intensity, shorter recoveries) must be carefully controlled during the first ten days of altitude training (cf. Bueno, 1998, p. 14).

It is known from training theory that stressing the development of one system (aerobic endurance) always occurs at the cost of other systems. A limited load on the movement apparatus therefore contains the risk that qualities in the speed range can be lost and technical development (coordination of speed, strength and technique) will suffer. To overcome this problem at altitude anaerobic alactic

speed training (short distances, long recoveries, limited volume) should be regularly conducted (cf. Bueno, 1998, p. 14).

Although the total volume of anaerobic training must be carefully distributed at altitude, it is important in endurance events that last less than 30 minutes to develop speed endurance and specific endurance. This is particularly important at altitude prior to main competitions and should take place by using shorter runs with longer recoveries than at sea level. This type of training can take place only during the last third of an altitude stay. Training sessions with runs close to race speed can be included in the second half of an altitude stay for events over 30 minutes in duration (cf. Bueno, 1998, p. 14).

6 Structure of training at altitude

Two to three days of regenerative activities prior to the departure to altitude have a positive influence on rapid acclimatization (cf. Bueno, 1997, p. 14).

Soviet coaching experience has shown that the first acclimatization phase at altitude lasts 7-10 days for young athletes and 3-4 days for top performers. The second phase takes for young athletes 5-8 days, for top performers 2-4 days. Normal training loads can be applied during the third phase (cf. Karikoski, 1983, p. 26).

The first phase includes walking and slow pace running. The duration of the runs is gradually increased but not the pace.

During the second phase the volume of medium intensity runs (pulse rate

140-160) is increased considerably but fast cross-country running (pulse rate over 160 a minute) is not recommended. Some interval training over shorter distances (100-200 m) with relatively long recoveries can be used towards the end of the second phase.

Training, as already mentioned, turns to almost normal in the third phase (cf. Karikosk, 1983, p. 26). For elite middle and long-distance runners this means that the first proper repetition session can be carried out on the 7th day after getting to altitude. After that time, training can be done to the normal sort of pattern one would use anywhere else, but with rather less intensity. So, one is definitely running slower if one is having a hard 10,000 m type of session (e. g. 8 x 1,000 m). Then one might find that one is working hard to run 2:48-2:50 min/km, while one is used to running something like 2:42 min/km. If, however, the athlete is only running 400 m intervals, then nothing will be affected much, because, for a single 400 m, the oxygen intake is of almost no importance. But even after these shorter intervals recovery time is longer at altitude (cf. Alford, 1994, pp. 39-40).

During the last two days of altitude training the athlete should recover (cf. Bueno, 1998, p. 12).

7 Nutrition at altitude

According to Franke (2000, pp. 79-80), the increased water and electrolyte losses and the increased breakdown of muscle glycogen at altitude requires an adequate electrolyte and fluid substitution as well as an increased intake of carbohydrates par-

ticularly following intensive exercise. Another physiological reason for a high carbohydrate/low-fat diet at altitude is that such a diet results in an increase in the respiratory quotient. This in turn means that for a given PCO_2 (or ventilation) the PO_2 will be higher. In other words, carbohydrates are an economical energy source because they require less oxygen than fats for energy production (cf. Bueno, 1998, p. 14). There is also the possibility that fat is less well absorbed than carbohydrate at altitude. There is no evidence that extra vitamins are beneficial if subjects are on a good mixed diet (cf. Milledge, 1994, p. 224; Alford, 1994, p. 41).

8 Re-acclimatization

According to Suslov (1994, pp. 48-49), during the period of re-acclimatization after a 2-5 weeks stay at altitude, work capacity, in terms of competition and test indicators, is of an undulating character.

The first few days after returning from altitude are often affected by problems relating to travel and, perhaps, a change in the time zone. This means that hard loads and high lactate values should be avoided (cf. Bueno, 1998, p. 12).

Popov (1994, p. 20), on the other hand, has found out that between days 1 and 3 the first peak after return from altitude occurs. Participation in competition is then possible if

- the place of the competition is fairly near and there will be no difficulties of travel or accommodation,

- the competition is not very important,
- the training program will proceed according to the level of the future competitions, after a period of about 3-4 weeks.

Suslov (1994, p. 49) has observed the first phase of enhanced work capacity during days 3-7. However, this is often followed, during days 8-10, by a phase of reduced performance. From days 12-13, work capacity continues to improve which means that training loads can again be increased. The first real peak performance phase takes place between days 14 and 25 after the return with days 18-20 probably being best suited for top performances. Popov (1994, p. 21), too, states that, in his experience, more than 80% of the best performances are achieved between the 18th and 21st day. This period should, therefore, coincide with the most important competition of the year. Bueno (1998, p. 11) suggests that day 17 after the return to sea level might be the ideal time for attempting top-level performances.

After some reduced performance capacity days there is another upsurge in performance between day 36 and 48 (Suslov, 1994, p. 49).

9 General recommendations

Although most experts do not recommend altitude training for young athletes (cf. Bueno, 1998, p. 14), there are completely different opinions of this aspect. For example, Bruce Tulloh says: "I think there is something to be said for introducing potential internationals at the age of 18-19 to alti-

tude training, because then they get the experience of how they respond. Then, 2-3 years later, if they are really hoping to attain international class, they at least know they are not going to waste their first trip to altitude. What you do find is that some young lad finds that this year he has a chance of making the international team, and so he decides to go about it. And I have noticed that the people who had been to Albuquerque with George Gandy seem to be getting much better results now; this is the 3rd year of their going to that place, and they have now learnt what to do before and after." (Alford, 1994, p. 41)

To sum it up then, opinions are very controversial concerning the methods and effects of altitude training. Even well-trained and altitude-experienced athletes are not protected against negative effects of the acclimatization phase at altitude, although the effects last only a short time. While special preparations prior to the departure are not absolutely necessary, some precautionary measures are still advisable. Athletes should be in a well-trained state, particularly as far as endurance capacities are concerned, before leaving to altitude. Another assumption is good health, because even small infections, common cold or not completely healed injuries can badly deteriorate at altitude. Departure to altitude should not take place in competition or during a period of training-created fatigue.

According to Martin (1994, p. 56), the key points to remember, for adding altitude to a training macrocycle, are the following:

- Do not wait until it is time to prepare for an important championship to try altitude training for the first time.
- Use laboratory physiological testing before going and after returning, to quantify the extent of change (in such variables as VO_{2max} , anaerobic threshold, and hemoglobin).
- Do not go so high or train so hard that the altitude stress is excessive.
- Ensure that the terrain used for training permits the option for flat as well as hilly running.
- Stay long enough to acquire sufficient adaptation to make the effort worthwhile.
- Create a home-like lifestyle and an entirely hospitable training environment by thorough advance planning (including a prior 'tourist trip' to the locale for initial arrangements and developing useful personal contacts).
- If the important competitions following altitude training are planned for sea level, return home early enough (roughly two weeks) to permit appropriate sea-level ventilatory and neuromuscular adaptation before racing begins.

Altitude Training for Sprinters?

Excellent performances in the sprint events are possible at altitude because of the lower resistance of the air at medium altitude. However, there is still much controversy about the effectiveness of altitude training for the sprint events, especially for the short sprints. In the opinion of Nikola Antonov, personal coach of Peter Petrov, bronze medallist in the 100 m at the Moscow Olympics of 1980, preparation for the sprint events without the use of altitude training is not so effective (cf. Antonov, 1994, p. 59). He recommends altitude training three times a year, with a total duration of 60-70 days. In a double periodization program, with a view to participation in the European or World Indoor Championships, the three altitude training camps, each of 20-22 days duration, are allocated as follows:

- The first camp starts in the middle of October or November, depending on when the training year begins.
- The second camp takes place in March or at the beginning of April, depending on the dates of the most important competitions, in this case the European or World Indoor Championships. Immediately after these, there is a week's transition period and then altitude training is resumed in Belmeken.
- The third camp starts at the end of June or July, or at the beginning of August, depending on the dates of the most important competitions of the year.

Prior to the first altitude training camp, a mesocycle of 15-20 days of general preparation is introduced. In the case of Peter Petrov, this preliminary preparation lasted a full month, because of his inherent low aerobic capacity.

The best effect of these three weeks of altitude training is obtained with the following methodical structure of organization in each microcycle:

- The aim in the first week is to gain a fast adaptation to a larger volume of training of the optimum intensity, according to the pertinent training mesocycle. Here, a wide variety of training means are used.
- During the second week the condition of the athlete must be watched carefully, because physiological changes now occur, due to the effect of acclimatization and the large training loads. During and after this week, 15 training sessions can be undertaken, varying the type of training load and, occasionally, including three or four training sessions in one day. Generally, 3-5 of these 15 training sessions are loaded heavily and they have a significant effect, structurally and functionally, on the athlete's organism. Four to six training sessions are given a medium loading and 4-6 a low loading, which activates the rehabilitation process and prepares the athlete for further heavy loads.

The structure and contents of the second weekly cycle of 18 training sessions, during the October training camp in Belmeken, for Peter Petrov, are presented on the following page (cf. Antonov, 1994, pp. 60-61).

Monday

First training session (from 10 a.m. to 12 noon):

- (1) Warm-up with slow running plus flexibility exercises with medicine balls.
- (2) Maximum and dynamic weight training – 6 tons.
- (3) Game – 30 min.
- (4) Flexibility exercises – 30 min.

Second training session (from 4 to 6 p.m.):

- (1) Fartlek on track – 3 x 2 km.
- (2) General physical preparation – 20 min.
- (3) Stretching – 15 min.

Tuesday

First training session (from 7 to 8 a.m.):

- (1) Slow steady run – 2 km.
- (2) Stretching – 10 min.
- (3) Vertical bounds – 120.

Second training session (from 9.30 a.m. to 12 noon):

- (1) Warm-up for speed work – 1 hour.
- (2) Standing and crouch starts, with and without towing a car wheel:
20 m at 85-95% effort, with 3-4 sets of 18 repetitions.
- (3) Standing start repetitions: 2 sets of 3 x 50 m.

Third training session (from 4 to 6 p.m.):

- (1) Warm-up – 45 min.
- (2) Acceleration runs – 4 x 50 m.
- (3) Fast reaction exercises.
- (4) Multi-jumps – 250.
- (5) Throws with a 4 kg shot – 20.
- (6) Tempo endurance – 10 x 200 m at 80% effort.

Fourth training session (from 8.30 to 9.15 p.m.):

- Swimming – slow and steady for the development of aerobic capacity.

Wednesday

First training session (from 7 to 8 a.m.):

Gymnastics, stretching and bounding.

Second training session (from 10 a.m. to 12 noon):

Speed endurance – 2 x 250 m at 85% effort; 2 x 200 m at 85% effort and 4 x 150 m at 90% effort.

Third training session (from 4 to 6 p.m.):

- (1) Basketball – 30 min.
- (2) Flexibility, stretching – 20 min.
- (3) Strength endurance uphill repetitions – 800 m.

Fourth training session (from 8.30 to 9.15 p.m.):

Swimming.

Thursday

First training session (from 7 to 8 a.m.):

- (1) Compensatory, slow steady run – 30 min.
- (2) Flexibility, stretching, relaxation – 30 min.

Second training session (from 10 a.m. to 12 noon):

- (1) Maximum and dynamic weight training – 6 tons.
- (2) General physical preparation – 30 min.
- (3) Tempo endurance – 3 sets of 4 x 100 m.

Friday

Three training sessions as for Tuesday, with modifications to the intensity of effort.

Saturday

Three training sessions as for Wednesday, with modifications to the intensity and length of the repetitions.

Sunday

One compensatory training session – slow, steady run – 30 min, plus flexibility and stretching – 30 min.

General Theme

ALTITUDE EFFECTS AND ADAPTATIONS

1 The hypobaric environment

As an individual ascends above sea level, barometric pressure is reduced relative to the magnitude of the elevation. Because the weight of the upper atmosphere compresses the weight of the lower atmosphere, barometric pressure decreases rapidly as one ascends from sea level. However, the composition of the air remains the same as it was at sea level: 20.93% oxygen, 0.03% carbon dioxide, and 79.04% nitrogen. The partial pressure of each gas is reduced in direct proportion to the increase in altitude. The reduced partial pressure of oxygen (PO_2) results in a reduced pressure gradient, which impedes oxygen diffusion from the blood to the tissues.

In addition to reduced oxygen availability at altitude, other environmental issues appear to pose significant hurdles for performance at high elevations. As ambient temperature is reduced during elevation, the amount of water vapor per unit volume of gas is also reduced. The low humidity seen at altitude results in a large evaporative heat loss caused by ventilation of the dry inspired air. The risk of dehydration at altitude is great even at rest, but during exercise when the ventilation rate is further elevated, the risk becomes even more significant. As acclimatization seems unable to reduce this chronic volume depletion, there is the need for high fluid intake, even when the thirst drive is absent (cf. Hoffman, 2002, pp. 248-249).

2 Physiological responses to altitude

The physiological stress associated with altitude is manifested primarily in its effect on oxygen availability to the tissues. When oxygen levels are reduced in arterial blood, inspired gases, or tissues, a situation of hypoxia is present. According to Wilmore & Costill (1999, pp. 347-350), acute hypoxia, which occurs when an individual is initially exposed to altitude, results in a number of responses that can affect performance:

- respiratory responses,
- cardiovascular responses, and
- metabolic responses.

2.1 Respiratory responses to altitude

Pulmonary ventilation

Pulmonary ventilation (breathing) increases at higher altitudes, both at rest and during exercise. Because the number of oxygen molecules in a given volume of air is less at higher altitudes, more air must be inspired to supply as much oxygen as during normal breathing at sea level.

As air is less dense at altitude, ventilation increases to bring in a larger volume of air.

Increased ventilation, or hyperventilation, results in a reduction of the amount of carbondioxide in the alveoli. Carbon dioxide follows the pressure gradient, so more diffuses out of the blood, where its pressure is relatively high, and into the lungs to be exhaled. This increased carbon diox-

ide clearance allows blood pH to increase, a condition called respiratory alkalosis. In an effort to prevent this condition, the kidneys excrete more bicarbonate ions. As bicarbonate ions buffer the carbonic acid formed from carbon dioxide, a reduction in bicarbonate ion concentration reduces the blood's buffering capacity. More acid remains in the blood, and the alkalosis can be reversed.

Pulmonary diffusion and oxygen transport

While the PO_2 at sea level is 159 mmHg it drops to 125 mmHg at an elevation of 2,439 m. As a result, the PO_2 within the alveoli and the pulmonary capillaries also decreases. Consequently, hemoglobin saturation drops from about 98% at sea level to approximately 92% at an elevation of 2,439 m.

Gas exchange at the muscles

Arterial PO_2 at sea level is about 104 mmHg, and the PO_2 in body tissues is consistently about 40 mmHg at rest, so the difference, or the pressure gradient, between the arterial PO_2 and the tissue PO_2 at sea level is about 64 mmHg. However, when one moves to an elevation of 2,439 m, the arterial PO_2 drops to about 60 mmHg, while the tissue PO_2 remains at 40 mmHg. Thus, the pressure gradient decreases from 64 mmHg at sea level to only 20 mmHg at the higher altitude, which is an almost 70% reduction in the diffusion gradient. Because the diffusion gradient is responsible for driving oxygen from the blood into the tissues, this change in

arterial PO_2 at altitude is an even greater consideration than the small 5-6% reduction in hemoglobin saturation that occurs.

Maximal oxygen uptake

Maximal oxygen uptake (VO_{2max}) decreases as altitude increases. VO_{2max} decreases little until the atmospheric PO_2 drops below 125 mmHg, which generally occurs at an altitude of 1,600 m. Specifically, VO_{2max} decreases at a progressively greater rate (exponentially) as the PO_2 drops with increasing altitude. Below 1,600 m altitude appears to have little effect on VO_{2max} and endurance performance. Above 1,600 m, however, VO_{2max} decreases approximately 11% for every 1,000 m.

2.2 Cardiovascular responses to altitude

Blood volume

Soon after arriving at altitude, a person's plasma volume begins to progressively decrease, before it plateaus by the end of the first weeks. Initially, the result of this plasma loss is an increase in the number of red blood cells per unit of blood, allowing more oxygen to be delivered to the muscles for a given cardiac output. Because this reduction in plasma volume occurs with little or no change in the total red blood cell count, it results in a higher hematocrit (the percentage of total blood volume composed of erythrocytes) but a smaller total blood volume than at lower altitudes. The diminished plasma volume eventually returns to normal levels. In addition,

continued exposure to high altitude triggers increased red blood cell production, so the total number of red blood cells increases. These adaptations ultimately result in a greater total blood volume, which allows the person to partially compensate for the lower PO_2 experienced at altitude. At the same time, however, blood viscosity increases, which can impair blood flow during near-maximal levels of exercise.

Cardiac output

A logical means to compensate for the limitation of the amount of oxygen carried to the muscles by a given volume of blood at altitude is to increase the volume of blood delivered to the active muscles. At rest and during submaximal exercise, this is accomplished by increasing cardiac output, the product of stroke volume and heart rate.

Standardized submaximal exercise performed during the first few hours at altitude results in an increased heart rate but decreased stroke volume (due to the reduced plasma volume). Fortunately, the rise in heart rate is sufficient to compensate for the drop in stroke volume and to slightly increase cardiac output. After a few days at altitude, the muscles begin to extract more oxygen from the blood, which reduces the demand for increased cardiac output, in turn reducing the need for an elevated heart rate. It has been shown that after ten days at high altitude, cardiac output during a given exercise bout is lower than it was at sea level before these adaptations to altitude occurred.

At maximal or exhaustive work levels at higher altitudes, both maximal stroke volume and maximal heart rate decrease. The dehydration experienced during ascent to high altitude results in a reduction in plasma volume and stroke volume. The body also appears to dump plasma volume during the first 24-48 h at altitude, thus contributing to the decrease in stroke volume. In addition, it has been suggested that maximal heart rate may be somewhat lower at high altitude as a consequence of a decrease in the response to sympathetic nervous activity, possibly due to a reduction in beta receptors (receptors in the heart that respond to sympathetic nerve activation, thus increasing the heart rate). The subsequent effect of these changes in maximal heart rate and stroke volume is obvious: Maximal cardiac output decreases.

With a decreased diffusion gradient to push oxygen from the blood into the muscles coupled with this reduction in maximal cardiac output, it can easily be understood why both VO_{2max} and aerobic performance are hindered at altitude. Thus, hypobaric conditions significantly limit oxygen delivery to the muscles, reducing the capacity to perform high-intensity aerobic activities.

2.3 Metabolic responses to altitude

Because oxygen delivery is restricted at altitude, oxidative capacity is decreased. More anaerobic energy production must occur, as evidenced by increased blood lactate levels for a given submaximal work rate. However, at maximal work rates, lactate

levels are lower than at sea level. This is paradoxical because, with limited oxygen uptake and increased reliance on anaerobic energy production, the muscles should be expected to produce more, rather than less, lactate for a given all-out effort. This phenomenon might be related to decreased muscle glycolytic enzyme activities, reduced buffering capacity, or the reduced power output that occurs in an all-out effort at altitude rather than at sea level. However, at this time there does not appear to be a really convincing explanation for the paradox of lower lactate at altitude (cf. Wilmore & Costill, 1999, p. 351).

3 Performance at altitude

3.1 Endurance activity

Obviously, activities of long duration that place considerable demands on oxygen transport and the aerobic energy system are the most severely affected by the hypobaric conditions at altitude. Because VO_{2max} is reduced by a certain percentage, individuals with larger aerobic capacities can perform a standard work task with less cardiovascular stress at altitude than those with lower VO_{2max} values (cf. Wilmore & Costill, 1999, p. 351).

3.2 Anaerobic sprinting, jumping, and throwing activities

Whereas endurance events are impaired at moderate altitude, this is generally not the case with anaerobic sprint activities that last less than a minute. Such activities place minimal demands on the oxygen transport

system and aerobic metabolism. Instead, most of the energy is provided through the ATP-PCr and glycolytic systems.

In addition, the thinner air at altitude provides less aerodynamic resistance to athletes' movements. Because of the reduced air resistance and reduced gravitational pull, performance in throwing events may improve on ascent to altitude, though events that require the thrown object to gain lift from the air (e. g., discus) may gain little (cf. Wilmore & Costill, 1999, p. 351).

4 Altitude acclimatization

When people are exposed to altitude for days and weeks, their bodies gradually adjust to the lower oxygen tension in the air. However, full compensation for hypoxia is not possible. Even endurance-trained athletes who live at altitude for years never attain the level of performance or the VO_{2max} values that they might achieve at sea level. According to Wilmore & Costill (1999, pp. 352-354), the adaptations that occur with prolonged altitude exposure are primarily:

- blood adaptations,
- muscle adaptations, and
- cardiorespiratory adaptations.

4.1 Blood adaptations

During the first weeks at altitude, the number of circulating erythrocytes (red blood cells) increases. The lack of oxygen at altitude stimulates the release of erythropoietin, the hormone

responsible for stimulating erythrocyte production. During six weeks of exposure to the Peruvian altitude (ca. 4,540 m), sea-level residents have shown remarkable increases in their hematocrits (the percentage of total blood volume composed of erythrocytes), up to an average of 59%.

As the volume of erythrocytes increases, so does the blood's hemoglobin content. Blood hemoglobin concentration tends to increase proportionately with increases in elevation. These adaptations improve the oxygen-carrying capacity of a fixed volume of blood.

4.2 Muscle adaptations

Although few attempts have been made to study muscular changes that occur during exposure to altitude, sufficient muscle biopsy data indicate that muscles undergo significant structural and metabolic changes during ascent to altitude:

- Muscle fiber area decreases, thus decreasing total muscle area.
- Capillary density in the muscles increases, which allows more blood and oxygen to be delivered to the muscles.
- The metabolic potential of the muscles is reduced.

The last-mentioned point suggests that, in addition to receiving less oxygen, muscles lose some of their capacity to perform oxidative phosphorylation and to perform both aerobic and anaerobic exercise.

4.3 Cardiorespiratory adaptations

One of the most important adaptations to altitude is an increase in pulmonary ventilation, both at rest and during exercise. Ventilation is stimulated by the decreased oxygen content of the inspired air at altitude. However, as noted above, such hyperventilation also promotes the unloading of CO₂ and the alkalization of blood. To prevent the blood from becoming abnormally alkaline, the amount of blood bicarbonate decreases rapidly during the first few days at altitude and remains depressed throughout the stay at high elevations.

5 Training at altitude for improved sea-level performance (including the “living high/training low” approach)

The physiological adaptations seen during acclimatization at altitude have led many scientists to hypothesize that either living or training at altitude, or a combination of the two, would enhance endurance performance at sea level. Hoffman (2002, p. 256) points out that, theoretically, the physiological adaptations to altitude (caused by the hypobaric hypoxic conditions) are similar to the stimulus causing physiological adaptations to endurance training. Several studies have examined different strategies employed to elicit a training effect:

- “Living high/training low”, meaning that the athlete resides at a moderate altitude but trains at a lower altitude.

- “Living high/training high”, in which the athlete resides and trains at moderate altitude.
- “Living low/training high”, in which the athlete lives at sea level but trains at a moderate altitude.

Although the practice of using altitude as an aid to improving sea-level endurance performance in athletes is extremely popular, suspicion continues to exist as to whether altitude acclimatization has any redeeming positive benefits to sea-level performance (cf. Bailey & Davies, 1997, p. 189; Green, 2000, p. 299). Many of the studies examining the effects of “training high” have suffered from experimental design problems. In addition, athletes find it difficult to maintain the same exercise intensity at elevation as at sea level (cf. Chapman & Levine, 2000, p. 452). As a result, the quality of the workouts performed at elevation is reduced, and the training stimulus to enhance the physiological adaptations will thus be inferior to that occurring at sea level.

In a recent well-designed study, athletes living at a moderate altitude (2,500 m) but training at a low elevation (1,250 m) exhibited significantly greater performance improvements than athletes “living high/training high” or “living low/training low” (Levine & Stray-Gundersen, 1997, p. 108). In that study, 41 distance runners were recruited from running teams and clubs and 39 (27 men, 12 women, age: 18-31 y) completed the study. Athletes were required to have a recent 5000 m running time of < 16:30 for men or < 18:30 for women, to be resident at sea level, and to have

been above 1500 m for > 1 week in the previous ten months. All athletes had a supervised 6-week period of training and laboratory familiarization at sea level and were randomly assigned to high-low (living at 2,500 m and training for four weeks at 1,200-1,400 m), high-high (living and training at 2,500-2,700 m) or low-low (living and training at 150 m). 5000 m time trials took place in Dallas on days 3 and 7 after return from field training. Blood volume and submaximal exercise performance were measured on day 2, and VO_{2max} on day 4. Both groups that lived at altitude significantly improved their VO_{2max} (5%), and these improvements were significantly correlated to increases in red cell volume (9%, $r = 0.37$, $p < 0.05$). In addition, race times for the 5K run were significantly reduced (13.4 ± 10 sec) in the high/low group only. Green (1998, p. 144) called this study by Levine & Stray-Gundersen the most rigorous investigation conducted to date. It shows that training at low altitude is necessary for exploiting the adaptations made to living at moderate altitude, at least for performance of 5000 m runs.

These same researchers then performed a retrospective examination of their studies by dividing the subjects into two groups: those they deemed responders to altitude training and those they deemed non-responders (Chapman, Stray-Gundersen & Levine, 1998, p. 1450). Responders were those athletes who improved their 5K run times by more than 14.1 sec, whereas non-responders improved less than 14.1 sec. Although both groups exhibited significant increases in erythropoietin concentra-

tions after 30 h at 2,500 m, the responders had a significantly higher erythropoietin concentration than the non-responders. After 14 days at altitude, erythropoietin levels had declined to baseline levels in non-responders but were still significantly elevated in the responders. As a result, the responders had a 7.9% increase in red blood cell volume and a 6.5% increase in VO_{2max} . Non-responders did not have an increase in either red blood cell volume or VO_{2max} . It is possible that erythropoietin may need to reach a threshold concentration before it is able to stimulate the production of additional red blood cells and provide an ergogenic effect for performance at sea level (Chapman & Levine, 2000, p. 454).

To sum it up then, most studies show that training at altitude leads to no significant improvement in sea-level performance. The physiological changes that do occur are transient but could offer an advantage during the first few days (or even weeks) after returning to sea level. This is still an area of debate. Living at high altitudes and training at low altitudes may be the best alternative (cf. Wilmore & Costill, 1999, p. 356). Nevertheless, even with advantage being inconclusive, altitude training will continue to be used by athletes in a variety of sports. Possibly the best way to look at altitude training is to treat it like any other type of training. It works better for some people than it does for others. How it is employed makes a considerable difference in the outcome (cf. Daniels, 1990, p. 20).

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