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Quantifying training intensity distribution in elite endurance athletes: is there evidence for an "optimal" distribution?

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This study was designed to quantify the daily distribution of training intensity in a group of well-trained junior cross-country skiers and compare the results of three different methods of training intensity quantification. Eleven male athletes performed treadmill tests to exhaustion to determine heart rate and VO_2 corresponding to ventilatory thresholds (VT_1, VT_2), maximal oxygen consumption (VO_{2max}), and maximal heart rate. VT_1 and VT_2 were used to delineate three intensity zones. During the same time period, all training sessions ($N = 384$, 37 strength training, 347 endurance) performed over 32 consecutive days were quantified using continuous heart rate registration and session Rating of Perceived Exertion (RPE). In addition, a subset of 60 consecutive training sessions was quantified using blood lactate measurements. Intensity distribution across endurance training sessions ($n = 318$) was similar when based on heart rate analysis ($75 \pm 3\%$, zone 1; $8 \pm 3\%$, zone 2; $17 \pm 4\%$, zone 3) or session RPE ($76 \pm 4\%$, zone 1; $6 \pm 5\%$, zone 2; $18 \pm 7\%$, zone 3). Similarly, from measurements of 60 consecutive sessions, 71% were performed with ≤ 2.0 mM blood lactate, 7% between 2 and 4 mM, and 22% with over 4 mM (mean $= 9.5 \pm 2.8$ mM). In this group of nationally competitive junior skiers, training was organized after a *polarized* pattern, with most sessions performed clearly below (about 75%) or with substantial periods above (15–20%) the lactate accommodation zone, which is bounded by VT_1 and VT_2. The pattern quantified here is similar to that reported in observational studies of elite endurance athletes across several sports. It appears that elite endurance athletes train surprisingly little at the lactate threshold intensity.

There is general agreement regarding the physiological factors limiting endurance performance (Pate & Kiska, 1984; Coyle, 1995; Hawley & Stepto, 2001). However, debate continues about how the daily training process should be organized to best develop these components and improve performance. Of the essential training variables, exercise intensity and its distribution is probably the most critical and most heavily debated.

We propose that two basic patterns of training intensity distribution emerge from the research literature (Fig. 1). The *threshold*-training model emerges from a number of studies demonstrating significant improvements among untrained subjects training at their lactate threshold intensity (Kindermann et al., 1979; Denis et al., 1984; Londeree, 1997; Gaskill et al., 2001). In this pattern of training organization, training at intensities at or very near the lactate threshold is emphasized. In contrast, a *polarized*-training model emerges from a limited number of published observations of international class rowers (Steinacker, 1993; Steinacker et al., 1998), gold medal winning time-trial cyclists (Schumacker & Mueller, 2002), and internationally elite marathoners (Billat et al., 2001). These studies suggest that at high-performance levels, athletes generally train below the lactate threshold intensity (perhaps 75% of the sessions or training distance), or clearly above the threshold intensity (15–20% of the time), but surprisingly little at their lactate threshold intensity. In essence, the training intensity distribution is polarized away from the moderately hard intensity range represented by the lactate threshold. This appears to be true even for marathoners of international class, who compete at an intensity approximating their lactate threshold (Billat et al., 2001).

Organizing the training intensity continuum into specific zones is common, with the zones often defined in terms of heart rate or blood lactate concentration ranges. Training zones have been recommended in coaching literature (Gaskill, 1998; Noakes, 2001) and national and international sports governing bodies have implemented standardized intensity-zone scales consisting of up to five different *aerobic* intensity zones. However, these numerous intensity zones suggest a degree of physiological specificity that is not really present, as the intensity

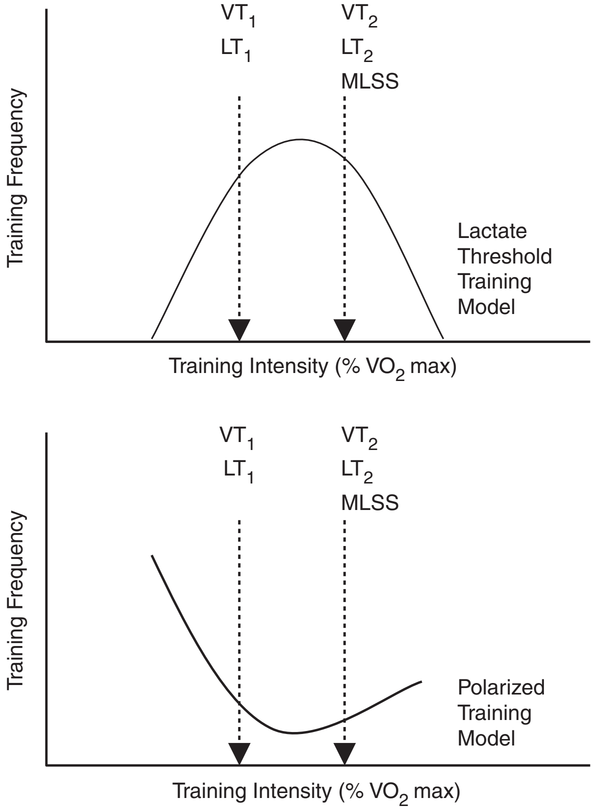

Fig. 1. Conceptual training intensity distributions associated with (a) the threshold training model – emphasizing training between the first and second lactate/ventilatory thresholds and (b) the polarized training model – emphasizing a large volume of training below the first lactate or ventilatory threshold combined with significant doses of training with loads eliciting 90–100% of VO_{2max}.

zone boundaries are not clearly anchored in underlying physiological events. Kindermann (Kindermann et al., 1979) first described the "aerobic–anaerobic transition" beginning with the *aerobic threshold,* marking the first increase in blood lactate, and ending with the *anaerobic threshold*, corresponding to the maximal lactate steady state. Studies using breath-by-breath gas exchange measurements (Lucía et al., 1998, 1999) have identified two specific ventilatory changes that correspond to the aerobic (LT_1) and anaerobic (LT_2) thresholds introduced by Kindermann and colleagues. These reproducible ventilatory changes are associated with simultaneous changes in blood lactate, EMG amplitude, and catecholamine concentration (Chwalbinska-Moneta et al., 1998). While questions remain regarding the cause–effect relationships among ventilatory, lactate, EMG, and sympathetic hormone changes, VT_1 and VT_2 appear to provide useful laboratory markers for the identification of three training intensity zones that are distinguished by meaningful differences in sympathetic stress load, motor unit involvement, and duration to fatigue. The ventilatory threshold approach to defining three intensity zones has been used by several groups in recent years (e.g. Boulay et al., 1997; Lucía et al., 1999; Fernandez et al., 2000), often for the purpose of describing intensity distribution in long endurance competitions. We have named these three intensity zones in terms of blood lactate characteristics: a *low lactate zone*, a *lactate accommodation zone* (where blood lactate concentration is elevated but production and removal rates re-establish equilibrium), and a *lactate accumulation zone*, where blood lactate production exceeds maximum clearance rates, and muscle fatigue is imminent.

In this study, we used the three intensity-zone model to quantify the training intensity distribution of a group of well-trained, male Norwegian cross-country skiers during a critical period of training preceding their competitive season. We hypothesized that these athletes would train according to a polarized model of training, where relatively little training was performed at lactate threshold intensity. We also compared training intensity distribution using three independent measurements: heart rate, blood lactate, and session perceived exertion.

Methods

Twelve male cross-country skiers, aged 17–18 years, volunteered to participate in the study, which was approved by the Human Research Ethics committee of the Department of Health and Sport, Agder University College. All subjects provided informed written consent prior to participation. The 12 subjects were students at a skiing high school in Norway and had been accepted for study there based in part on their skiing performance. The head coach of the program was a recent senior national team head coach. Among the subjects were athletes who were ranked numbers 1 and 2 in their age group for the "Norwegian Cup Series" the previous year. Several of the athletes from the school had been later taken up on the national team or developmental recruit teams. We assumed that this group would train in a manner consistent with the prevailing training philosophy among the highly successful Norwegian elite cross-country skiing milieu, which has won 14 gold, 13 silver, and six bronze medals in Olympic finals since 1992.

Intensity zone determination

The three intensity zones were established based on the results of treadmill testing performed halfway through the training quantification period. The athletes were in their third year at the high school and had all previously performed maximal treadmill testing. After a ~30-min competition warm-up, athletes performed a continuous treadmill test to voluntary exhaustion. Gas exchange data was collected breath-by-breath (Jaeger Oxycon Pro, Breda, the Netherlands) with calibration prior to each test. The treadmill (Woodway, Wel am Rhein, Germany) was maintained at 10% grade throughout the test, a standard method of testing XC skiers in Norway. The test was initiated with a 5-min period at a velocity of $6\,km\,h^{-1}$ to ensure stable baseline ventilatory measurements, followed by a $0.6\,km\,h^{-1}\,min^{-1}$ increase in velocity until exhaustion applied in 30-s increments. Maximal oxygen consumption (VO_{2max})

was defined as the highest 30-s average achieved during the test. The first ventilatory threshold (VT_1) was defined as an increase in $V_E \cdot VO_2^{-1}$ corresponding with a break in linearity in V_E, but without an increase in $V_E \cdot VCO_2^{-1}$. The second ventilatory threshold (VT_2) was defined as the intensity where $V_E \cdot VCO_2^{-1}$ also began to rise. Two independent observers made ventilatory threshold determinations. If there was disagreement between the two observers, a third was brought in. Heart rate was registered every 5 s via telemetry (Polar, Kempele, Finland) to determine heart rates corresponding to VT_1 and VT_2, as well as maximal heart rate (HR_{max}).

Registration of training intensity and duration

Before and after the day of treadmill testing, athletes performed their normal training regime. Care was taken not to influence their training and the investigators were careful not to discuss training methods or organization with the athletes before or during the data collection period. Athletes were provided detailed instructions via a group meeting with the investigator and written materials explaining the recording process. The athletes were provided simple PC spreadsheets for recording their daily training information. For 32 consecutive days, all training bouts were recorded. A training diary was maintained recording the mode of training, intended intensity (interval, steady state, strength training, etc.), and duration of each training session. Data was collected during late October and most of November, part of the pre-competition preparation period. During this time, athletes performed mostly running in hilly terrain, some roller skiing, and transitioned to on-snow skiing sessions as conditions permitted.

Heart rate

Heart rate was monitored for every training bout using downloadable, frequency coded heart watches (Polar S610) with 15-s registration intervals. Athletes were provided a numbered heart watch to keep for the duration of the collection period. An investigator downloaded heart rate data files weekly. Heart rate records were then matched against diary contents to ensure accurate registration.

Session RPE

Thirty minutes after every training session, each athlete recorded their rating of perceived exertion for the entire session using the modified 10-point scale developed by Foster and colleagues (Foster et al., 1996; Foster, 1998). In short, this method was designed to provide a measure of the global perception of the intensity, or physical stress, of an entire training session. Here, athletes were allowed to mark a plus sign along side the assigned value if they wished, which was then interpreted as 0.5 points (4.5 for example).

Blood lactate measurement

The coaches felt it would be overly invasive and impractical to perform blood lactate testing for each athlete every day over a 32-day period. Therefore, during the final week of data collection, an investigator was present at every training session and obtained blood lactate measurements from all the athletes. During training bouts characterized as steady-state workouts, measurements were made on a flat portion of the training course and between 20 and 60 min after exercise start. During interval-type training sessions, measurements were made 2 min after completion of a work bout, and after at least two interval bouts had been performed. Measurements were made under field conditions (0 to $-8\,^{\circ}C$) using methods previously validated for the Lactate Pro LT-1710™ (ArkRay Inc, Kyoto, Japan) by Medbø et al. (2000).

Training data analysis

Training duration was determined using both training diary and heart rate registration records to ensure agreement. In the few cases where there was a minor discrepancy between diary and heart rate registration, the average of the diary and heart rate download duration was taken. Training sessions were categorized according to five basic types: long distance, interval training, threshold sessions, speed sessions, and strength training. Strength training sessions were not included in the training intensity analysis.

Heart frequency data were downloaded and used to determine training intensity based on heart rates at VT_1 and VT_2 determined during laboratory testing. Training intensity distribution was quantified from heart rate using two different methods. In the first method, called "total time-in-zone," software provided by the heart watch manufacturer (Polar Precision Performance 3.0, Polar Inc., Kempele, Finland) was used to determine the percentage of training time spent in each of the three training zones for each individual training session. The average training time in each zone for all sessions was then determined.

In the second heart rate analysis, the "session–goal" method, we analyzed each training session according to the specific goals of steady state, threshold, and interval training sessions. The intensity zone of training sessions defined as "steady-state" or long-distance training was quantified using the average heart rate for the entire session. Training sessions involving a primary bout at a planned "threshold intensity" were quantified by averaging the heart rate data from the specific period(s) of work performed at goal intensity (for example, 30 min at "LT" preceded by a 20-min warm-up and followed by a 20-min cool down). The intensity of high intensity interval training sessions was quantified based on the average peak heart rate attained during each interval bout (for example, 6 × 5 min at "90% VO_{2max}" with 2-min recovery between bouts). Pilot testing of this approach during interval training sessions performed in the laboratory showed excellent correlation with the average peak oxygen consumption for the repeated work bouts of an interval session.

Session RPE data were divided into three intensity zones based on pilot work with another group of athletes performing laboratory training sessions. The 10-point scale was divided into three zones: zone 1, ≤ 4; $4 < \text{zone 2} < 7$; and zone 3, ≥ 7 (Fig. 2). Training zone identification based on heart rate was compared with that based on session RPE to determine the percent agreement for the two methods.

Blood lactate measurements, made on a continuous subset of 60 of the training sessions, were used to identify the training intensity zone for each session based on the following concentration values: zone 1, ≤ 2.0 mM, zone 2, >2.0 and <4.0 mM, zone 3, ≥ 4.0 mM.

Statistical analysis

Data are presented as means ± standard deviation with one exception; the subset of 60 training sessions in which heart rate, session RPE and blood lactate measurements were made is presented as the total distribution for all 60 sessions, not as the mean ± standard deviation of the 11 individual athlete's training intensity distributions, because of the small individual sample size of training sessions. Training intensity distribu-

0 - Rest

1 - Very easy

2 - Easy

3 - Moderate

4 - Somewhat Hard

VT_1

5 - Hard

6

VT_2

7 - Very Hard

8 - Very, Very Hard

9 - Nearly Maximal

10 - Maximal Effort

Fig. 2. The Session RPE scale developed by Foster (1998). The session RPE breakpoints corresponding to VT_1 and VT_2 intensity thresholds were determined based on preliminary studies in our laboratory as well as analysis of the present data.

tions determined using heart rate, session RPE, and blood lactate measurement were compared using the χ^2 test. A *P*-value of ≤ 0.05 was considered statistically significant.

Results

The physical characteristics of the subjects and maximal treadmill test results are presented in Table 1. The specific oxygen consumption and heart rate values identified at VT_1 and VT_2 are presented in Table 2. During the data collection period, 404 training sessions were quantified. Because data from one of the 12 subjects was incomplete because of a period of sickness, 20 training bouts recorded for this subject were excluded from the data. Of the 384 remaining sessions, 37 (9.6%) were identified as strength training, and the remaining 347 (90.4%) as endurance sessions of varying intensity. Only the endurance sessions were included in the training intensity distribution analysis.

Table 1. Physical characteristics of the subjects

$N = 11$	Mean ± standard deviation	Range
Age	17 ± 1	17–18
Height (cm)	180 ± 4	172–188
Weight (kg)	72.6 ± 5.7	63–83
VO_{2max} ($L\,min^{-1}$)	5.3 ± 0.5	4.6–6.3
VO_{2max} ($mL\,min^{-1}\,kg^{-1}$)	73 ± 4	69–80
V_{Emax}	181 ± 20	155–96
HR_{max}	198 ± 9	189–220

HR_{max}, maximal heart rate; VO_{2max}, maximal oxygen consumption.

Table 2. Physiological values corresponding to VT_1 and VT_2

	VT_1	VT_2
VO_2 ($mL\,min^{-1}\,kg^{-1}$)	54 ± 2	65 ± 4
% VO_{2max}	74 ± 2	89 ± 2
HR ($b\,min^{-1}$)	161 ± 9	181 ± 8
% HR_{max}	81 ± 2	91 ± 2

HR_{max}, maximal heart rate; VO_{2max}, maximal oxygen consumption; VT_1, first ventilatory threshold; VT_2, second ventilatory threshold.

Training characteristics

During the 32-day training quantification period, each athlete averaged 35 ± 4 total training sessions (range 30–41). Based on training diary records, 74.6% of the 347 endurance sessions were described as steady-state endurance sessions. Interval training made up 17% of the sessions, lactate threshold training 4.9%, and speed/sprint training 3.5%. The steady-state endurance sessions generally lasted 90–140 min, the hard interval sessions 70–100 min.

Heart rate-based training zone distribution

Based on the total time-in-zone method, 91% of all training time was spent at a heart rate below VT_1 intensity, 6.4% of endurance training time was between VT_1 and VT_2, and only 2.6% of all 15-s heart rate registrations were over the heart rate corresponding to VT_2. However, when heart rate data were analyzed using the session–goal method, the distribution of sessions shifted; 75 ± 3% of the sessions performed were under VT_1, 8 ± 3% included lengthy periods performed between VT_1 and VT_2, and 17 ± 4% of the training sessions were interval type bouts were heart rate during the work periods exceeded VT_2 intensity (Fig. 3). Steady-state endurance sessions were performed at an average heart rate of 66 ± 5% of HR_{max}. During interval sessions, heart rate reached an average of 93 ± 3% of HR_{max}.

Session RPE-based training intensity distribution

Of the 336 endurance training sessions where session RPE was correctly registered, 76 ± 4% were performed at an intensity of ≤ 4 on the 10-point scale shown in Fig. 3 (average rating 3.3 ± 0.6). Athletes rated 6 ± 5% of all sessions in the middle of the scale, between 4.5 and 6.5, and 18 ± 7% of the sessions were rated as ≥ 7 ("very hard" or harder,

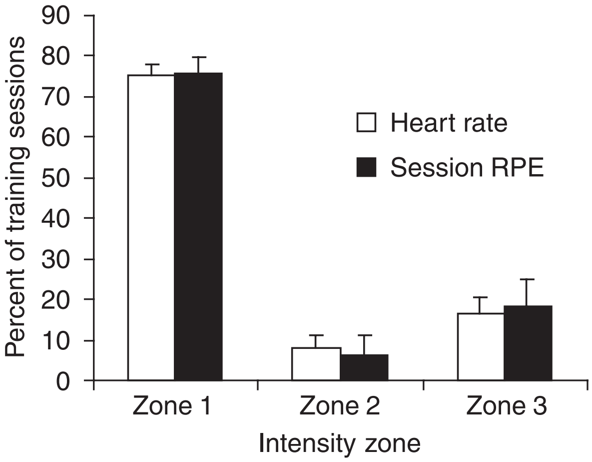

Fig. 3. Training intensity distribution in 318 training bouts where heart rate records were complete and session RPE was recorded. There was no significant difference in intensity distribution between session–goal heart rate analysis and session RPE.

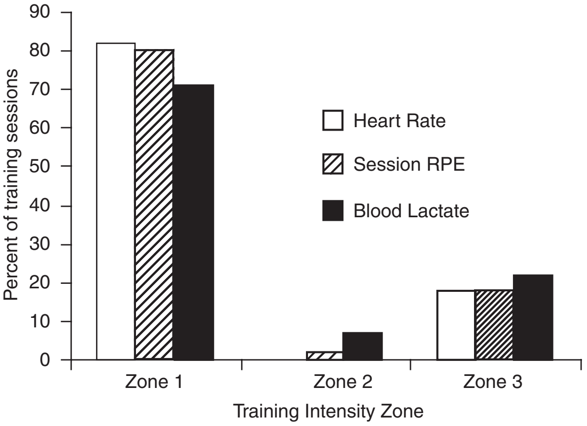

Fig. 4. Training intensity distribution for a continuous subset of 60 training sessions where heart rate, session RPE and blood lactate were recorded. There were no significant differences in intensity distribution among the three analysis methods. The heart rate bar is absent for zone 2 because none of the 60 sessions were identified in this zone based on heart rate.

average rating 7.4 ± 0.8, Fig. 3). For the 318 sessions where both complete heart rate and session RPE data were available, the agreement between the session-by-session heart rate quantification method and the session RPE method was 92%. There was no significant difference in training session distribution across intensity when comparing the session goal heart rate and session RPE methods.

Blood lactate measurements

Of 60 individual blood samples taken during the final week of training (each representing one training session for one athlete), 71% were under 2.0 mM (average 1.2 ± 0.4 mM), 7% were between 2 and 4 mM (average 2.7 ± 0.4 mM), and 22% were over 4 mM (average 9.5 ± 2.8 mM). Figure 4 presents the training intensity zone distribution for the 60 sessions in which all three classification methods were used. No significant differences in training distribution were observed among the three methods.

Discussion

The key finding of this study is that well-trained junior cross-country skiers, training in a manner consistent with the intensity distribution recommended for highly successful international cross-country skiers, adopt a polarized model of intensity distribution. About 75% of their training sessions are performed with essentially the entire session below the first ventilatory threshold (≤ 2.0 mM blood lactate). In 5–10% of training sessions, major portions of the training are performed between VT_1 and VT_2. The remaining 15–20% of training sessions are performed as interval bouts, with substantial periods of work above VT_2.

The quantification of daily training performed here appears to be one of the most rigorous available in the literature, with nearly 400 individual training sessions quantified over 32 consecutive days during an important period of competition preparation. However, this was not an experimental study. We did not compare the impact of two different training intensity distributions on performance enhancement. Experimental studies are extremely difficult to perform on high level athletes because neither the athletes nor their coaches wish to suddenly alter methods they have developed over perhaps years of coaching. The yearly training process at this level is indeed an experimental setting involving years of iterative adjustments to training in response to performance results. The training intensity distribution observed in these junior males skiers is very similar to the distribution of training observed in elite rowers (Steinacker, 1993; Steinacker et al., 1998), gold medal winning track cyclists (Schumacker & Mueller, 2002), and international class marathoners (Billat et al., 2001). Because this "75-5-20" distribution of training intensity across the three intensity zones demarcated by VT_1 and VT_2 emerges from several different studies of highly successful performers in different sports from different countries, we hypothesize that it approximates an optimal intensity distribution for training of high-performance endurance athletes. However, experimental studies comparing this intensity distribution with, for example, greater emphasis on training within the lactate accommodation zone, need to be performed. In addition, studies examining training intensity distribution during different phases of the training cycle are needed. The present study focused only on the pre-competition preparation period. One goal of future investigations should be to quantify to what extent training intensity distribution changes from the preparation period to the competitive period.

A potential shortcoming of the three intensity-zone quantification model used here is that training at very high intensities where heart rate is irrelevant is not incorporated into the quantification structure. For example, Paavolainen et al. (1999) have demonstrated that sprint and explosive plyometric type training can improve endurance performance, pointing to the role of neuromuscular factors in endurance performance. This type of training constituted only 3.5% of all endurance sessions quantified in the present study. It is unclear how these volumes of very high intensity, short duration training impact the total stress load on the endurance athlete.

Ventilatory thresholds were used as a surrogate measure for lactate thresholds when establishing exercise intensity zones. Ventilatory measurements provide two clearly defined physiological events that are practical to identify in a laboratory setting with modern breath-by-breath gas exchange measurement equipment. Corresponding lactate thresholds LT_1 and LT_2 (sometimes called the *aerobic* and *anaerobic* thresholds) are more difficult to define given that blood lactate concentration is a continuous function of increasing exercise intensity. The second threshold (LT_2) is sometimes fixed to a specific concentration such as 4.0 mM. However, this approach is imprecise given substantial individual and exercise mode (Beneke & Von Duvillard, 1996) variation in the lactate concentration corresponding to the maximum lactate steady state (MLSS). Lucia and colleagues have successfully used the ventilatory threshold approach to distinguish the physiological characteristics of professional and elite amateur cyclists (Lucía et al., 1998).

That VT_1 and VT_2 correspond to LT_1 and LT_2 is supported by studies of Lucía et al. (1999). They demonstrated that in 28 professional or elite amateur cyclists undergoing a continuous ramp test to exhaustion, there were no significant differences in the power output corresponding to VT_1, LT_1 or the root mean squared EMG amplitude threshold identified as EMG_{T1}. Further, there were no significant differences in power output corresponding to LT_2, VT_2, and EMG_{T2}. Chwalbinska-Moneta et al. (1998) have demonstrated a close correlation between lactate, EMG, and catecholamine thresholds. Together, these studies support LT_1/VT_1 and LT_2/VT_2 as defensible physiological anchor points for the establishment of three training intensity zones. In the present study, the field measurements of blood lactate during training were highly consistent with the ventilatory threshold determinations made in the laboratory, further supporting the validity of the approach. We chose blood lactate concentrations of 2.0 and 4.0 mM as estimates for LT_1 and LT_2, based on published studies (Lucía et al., 1999) and present results. These values appear to be reasonable for running, cross-country skiing, and rowing. However, for some individuals, and perhaps in general for activities like cycling and speedskating, the LT_2 (MLSS) may be substantially higher than 4 mM (Beneke & Von Duvillard, 1996).

The practical link between laboratory testing measurements and training quantification is often heart rate. Downloadable heart rate monitors make it possible to quantify the total time spent during a workout within any specific heart rate range. This function, combined with the identification of threshold heart rates, makes the determination of average heart rate for an exercise bout or ‘‘total time in zone’’ a practical and popular approach to evaluating training intensity. However, we found that this method agreed poorly with both session RPE and blood lactate measurements. Averaging heart rate over an entire session may underestimate the energetic and sympathetic stress of repeated high-intensity bouts such as interval training. In addition, well-trained athletes tend to spend more time warming up and cooling down at lower intensities, which will inflate the time spent in the lowest intensity zone. The session–goal method of heart rate analysis employed here resulted in a distribution of training intensity that was in close agreement with both the athletes' perception and lactate measurements taken during the various types of training performed.

The third intensity quantification approach used in this study was the session RPE method developed by Foster and colleagues. The session RPE method attempts to quantify the athlete's global perception of the stress of an entire training bout, based on an evaluation performed 30 min after training cessation. In studies of cyclists and speedskaters, Foster's group found session RPE multiplied by training duration to be a valid measure of training load, when compared with heart rate quantification. In a retrospective analysis, over 80% of upper respiratory tract infections incurred during the observation period were explained by preceding (within 10 days) elevations in training load quantified using session RPE (Foster, 1998). In our group of well-trained junior athletes, session RPE appeared to be a practical method of monitoring daily training stress that corresponded closely with heart rate and blood lactate measures. Intensity zone determinations based on session RPE and the session–goal heart rate method were in agreement for 92% of all sessions. In the remaining sessions, the session RPE method identified lower intensity zone than heart rate, perhaps because of heart rate drift over the course of a longer workout. Session RPE may be particularly useful in capturing elevations in exercise stress that are not because of acute intensity alone, but also because of the duration of an individual bout, and the background training load and accumulated fatigue experienced by the athlete.

Accepting that we have accurately quantified the day-to-day intensity of training in this group of successful junior athletes, the question remains "Why do successful endurance athletes train above and below their lactate threshold, but surprisingly little at their lactate threshold intensity?" From a biological perspective, the goal of training is to stimulate appropriate changes in gene expression and protein synthesis. This regular, cellular level stimulation must be achieved while preserving the autonomic balance of the organism so that over training is avoided and the capacity for maximal sympathetic mobilization is retained. This balance is severely challenged by elite endurance athletes. The practical manifestation of this interplay between training as cellular adaptive signal and training as negative stressor is the day-to-day manipulation of the intensity, frequency, and duration of exercise.

In untrained subjects, training for 2–3 months, 4–5 days per week at an intensity within the lactate accommodation zone has been shown to stimulate significant improvements in VO_{2max}, lactate or ventilatory thresholds, and endurance performance (e.g. Kindermann et al., 1979; Denis et al. 1984; Londeree, 1997; Gaskill et al., 2001). The intensity region at or near LT_2 represents the highest work rate that can be maintained for an extended period, making it an attractive intensity for daily training. However, in well-trained athletes training once or twice daily through most of the year, repeated training bouts at the lactate threshold might generate excessive sympathetic stress (Chwalbinska-Moneta et al., 1998) while still providing a sub-optimal stimulus for eliciting further gains in capacity (Londeree, 1997). Rather than train monotonically within the lactate accommodation zone, elite endurance athletes with unrestricted training time appear to select a training pattern involving the accumulation of large volumes of work at lower intensities combined with 1–3 weekly bouts where significant time is spent at intensities $\geq 90\%$ of VO_{2max}. High-performance endurance athletes have also gravitated toward multiple daily training sessions instead of one longer daily session. While experimental data is lacking, we assume that there are long-term advantages to this training approach since it has become so common. For example, multiple daily sessions, often at comparatively low intensity, may ensure a high degree of induction of genes for the synthesis of mitochondrial (and other relevant) proteins while ensuring better energy availability and less autonomic stress on the organism. In the present study, 75% of the training sessions were spent training at an intensity of $\sim 65\%$ VO_{2max}. For well-trained athletes with a high VO_{2max} (70–80 $mL\,kg^{-1}\,min^{-1}$ in this group), this "low" intensity still generates a high-oxidative flux in the working muscle. Assuming similar active muscle mass, the athletes here training at 65% of their maximal oxygen consumption would have about the same muscular oxidative flux as an untrained person performing at or near VO_{2max}. This magnitude of cellular energy turnover coupled with the relatively long duration the workloads are sustained appears sufficient to provide an effective stimulus for the induction of the various genes involved in mitochondrial biogenesis (Hood et al., 2000). This approach may be preferable in the long-term training of high-performance athletes since combining frequent bouts and moderately hard intensities on most days seems to increase the risk of over training (Bruin et al., 1994).

The hard training sessions quantified here were clearly quite demanding, consisting of repeated 4–8 min work bouts performed at $\geq 90\%$ of VO_{2max}. These sessions were also reasonably long, 70–100 min in total duration. While these high-intensity sessions are believed to be critical to achieving maximal performances, they cannot be performed optimally if intervening basic endurance sessions are performed at too high an intensity (Bruin et al., 1994). However, high-intensity training sessions appear to be well tolerated when variation in intensity of training is ensured (Lehmann et al., 1991, 1992). Less experienced athletes may tend to train harder than prescribed during low-intensity sessions and not hard enough during prescribed high-intensity sessions (Foster et al., 2001). The junior athletes in the present study, training under the close supervision of an experienced coach of elite athletes, appeared to manage their training intensity quite rigidly. Although they trained substantially fewer hours than top senior-age skiers (who train up to 25–30 h per week), their organization of training intensity was essentially the same as that recommended for the senior national team (personal communication).

Perspectives

While our knowledge of the physiology of endurance performance is becoming fairly detailed, systematic data linking the specific characteristics of training to continuing performance development is lacking. Understandably, data from elite athletes subjected to specific training interventions are scarce, as these individuals rarely wish to alter their training in the interest of science. Short-term training studies based on untrained, or moderately trained individuals should not be uncritically used as argumentation for the organization of training of elite athletes. Presently, we are left with observations of top performers, who constantly search for better training methods, as our best information for understanding optimal training organization. There is probably substantial individual variation in responsiveness to training so that no one distribution of training intensity is optimal for all athletes (Gaskill et al., 1999). However, the present results, coupled with other recent studies from divergent sports, point to a model of training organization in elite endurance athletes where training is predominantly performed *below* the first ventilatory or lactate threshold, or *above* the second threshold, but rarely at ''middle intensities''. The *Threshold* and *Polarized* training intensity distribution models provide a basic framework for future investigations exploring the endurance training process.

Key words: training zones, exercise intensity, lactate threshold, cross country skiing, perceived exertion.

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