Indirect EPOC Prediction Method Based on Heart Rate Measurement

White Paper by Firstbeat Technologies Ltd.

This white paper has been produced to review the method and empirical results of an indirect EPOC measurement method developed by Firstbeat Technologies Ltd. Parts of this paper may have been published elsewhere and are referred to in this document.

INTRODUCTION

This document describes a method for EPOC (excess post-exercise oxygen consumption) prediction based on heart rate (HR) measurement. EPOC is defined as the excess oxygen consumed during recovery from exercise as compared to resting oxygen consumption. The EPOC prediction method has been developed to provide a physiology-based measure for training load assessment.

Training load assessment

It is difficult to select an optimal exercise dose. Sufficiently strenuous exercise causes a disturbance in body's homeostasis which after recovery results in improved fitness (E.g. Brooks & Fahey 1984; Åstrand & Rodahl 1986). Too easy training does not improve fitness but too hard training may in long term lead to overtraining. It is therefore important to measure the training load.

Methods that are used in assessing training load may be broadly characterized as subjective and physiological measures. Subjective measures are easy to access, but do not always reflect physiological responses and recovery demand. Traditional physiological measures, such as VO2, heart rate and blood lactate, reflect mainly momentary intensity of exercise and not length of exercise or cumulative exercise load. There are also training load measures such as training impulse (TRIMP), but which does not have physiological basis or scale and therefore may be difficult to interpret.

EPOC is a physiological measure (amount of oxygen consumed in excess after exercise as measured in liters or ml/kg) that that reflects the recovery demand and the disturbance of body's homeostasis brought by the exercise. Measurement of EPOC has been possible only by analyzing respiratory gases with laboratory equipment, thus being expensive, time consuming and not applicable to everyday purposes.

The lack of valid and easy-to-apply physiology based method for the assessment of training load has led us to develop a method to estimate EPOC indirectly from heart rate measurement.

EPOC in exercise sciences

The first observation of an elevated resting metabolic rate after exercise was made in 1910 by Benedict and Carpenter and was later studied as "oxygen debt" (Hill and Lupton in 1923). The present name EPOC has been used not only to represent oxygen repayment during recovery but also to reflect the general exercise-induced disturbance of body's resting metabolism (Gaesser & Brooks 1984; Gore & Withers 1990) and resting homeostasis (Brehm & Gutin 1986): "the cause of Excessive Post-Exercise Oxygen Consumption (EPOC) is the general disturbance to homeostasis brought on by exercise" (Brooks & Fahey 1984).

EPOC reflects the body's recovery requirements after exercise. Active oxygen-consuming recovery processes occurring in the body are due to replenishment of body's resources (O_2-stores, ATP, CP) and increased metabolic rate (increased HR and respiratory work, elevated body temperature) caused by metabolic by-products and hormones produced during exercise. (Brooks & Fahey 1984; Åstrand & Rodahl 1986; Børsheim & Bahr 2003)

- EPOC reflects a general disturbance in body's homeostasis caused by exercise.
- EPOC is calculated by subtracting the area under resting VO_2 from the area under the recovery VO_2 curve (see Figures 1 and 4).
- EPOC gets higher with higher intensity and/or longer duration of exercise (e.g. Børsheim & Bahr 2003) (see Figures 3 and 4).

CONSTRUCTION OF THE MODEL FOR HEART RATE BASED EPOC PREDICTION

The EPOC model was constructed based on meta-analysis data of peer-reviewed articles. Only valid studies were carefully selected for this purpose. The data included 48 different exercise settings, including a total of 158 trained and untrained male and female subjects. Exercise durations ranged from 2 to 180 minutes and exercise intensities from 18 to 108% of VO_{2max}. The modeling data included both continuous and intermittent exercises and consisted of running, cycling and upper-body ergometer exercise.

EPOC is predicted only on the basis of heart rate derived information (see Figure 2). The variables used in the estimation are current intensity (%VO_{2max}) and duration of exercise (time between two sampling points, Δt) and EPOC in the previous sampling point. The model is able to predict the amount of EPOC at any given moment. No post-exercise measurement is needed (see Figure 1). The model can be mathematically described as follows:

$$EPOC_{(t)} = f(EPOC_{(t-1)}, exercise\_intensity_{(t)}, \Delta t). \quad (1)$$ (Saalasti 2003)

At low exercise intensity (<30-40%VO_{2max}), EPOC does not accumulate significantly after the initial increase at the beginning of exercise (see Figure 3). At higher exercise intensities (>50%VO_{2max}), EPOC accumulates continuously. The slope of accumulation gets steeper with increasing intensity.

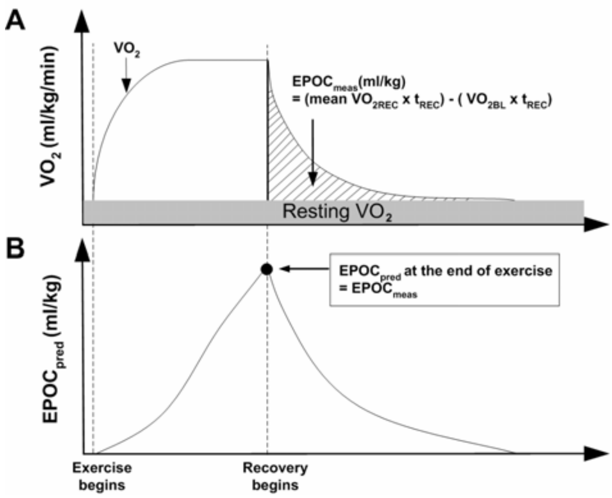

Figure 1 A. EPOC measured in laboratory ($EPOC_{meas}$). 2 B. Predicted EPOC based on heart rate derived information ($EPOC_{pred}$). EPOC prediction does not need any post-exercise measurements. VO_{2REC} = recovery VO_2, t_{REC} = recovery time, VO_{2BL} = Baseline (resting) VO_2.

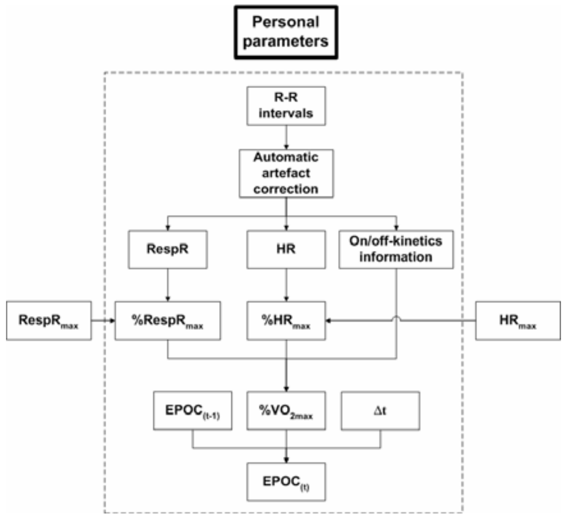

Figure 2. The estimation model of EPOC. $HR_{(max)}$ = (maximal) heart rate, $RespR_{(max)}$ = (maximal) respiration rate, %VO_{2max} = percentage of maximal oxygen uptake.

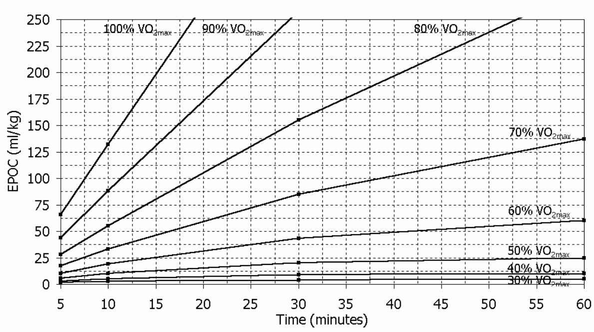

Figure 3. The accumulation pattern of EPOC at various intensities as a function of exercise duration.

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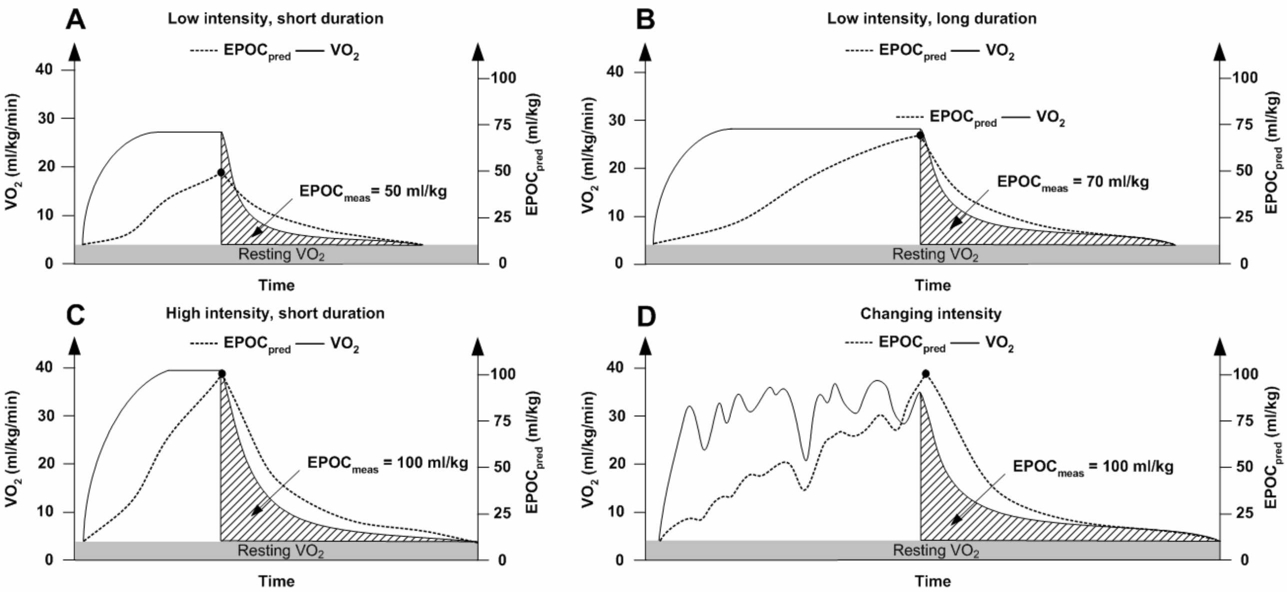

Figure 4. EPOC$_{meas}$ (shaded area) and EPOC$_{pred}$ (dotted line) from four sample exercises. Figures A to C represent typical constant-intensity exercises, whereas Figure D represents a typical exercise during which the intensity changes naturally, for example according to speed (e.g. running, cycling, skating or rowing), work rate (e.g. indoor rowing or cycle ergometry) or terrain (uphill/downhill).

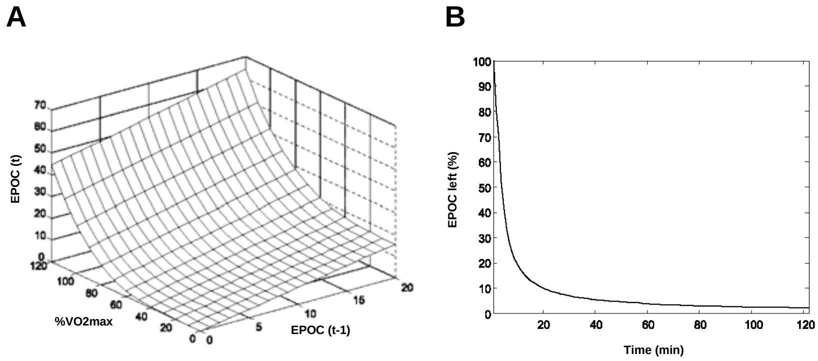

Figure 5. Calculation models of the EPOC$_{pred}$ upslope component (A) and downslope component (B), fitted using meta-analysis data. The combination of upslope and downslope equations determines the gradient of EPOC$_{pred}$ accumulation.

The accumulation formula of HR-based EPOC is a combination of upslope (Fig. 4 A) and downslope (Fig. 4 B) formulas. When the intensity of exercise is high, EPOC accumulates, whereas during periods of rest or low-intensity activity, the combination of these formulas results in decreasing EPOC.

There may be a time lag of about 15 s between the cessation of exercise and reaching the peak value of heart beat derived EPOC. This is due to the slow recovery pattern of VO_2 after exercise, which lags behind the true intensity (the calculation model is not able to recognize the exact end point of exercise).

MODEL VALIDATION (Data published, Rusko et al. 2003)

Methods

Subjects were 32 healthy adults (8 fit and 8 less fit males and females), age 38±9 years (mean±SD), weight 69.6±10.8 kg, height 171.6±8.5 cm and VO_{2max} 44.0±8.8 ml/kg/min. The procedure is presented in Figure 6. Measurements included two 10-min submaximal steady state exercise sessions at 40% and 70% VO_{2max}, with a constant load, and a maximal incremental bicycle ergometer (Ergoline, Bitz, Germany) test to voluntary exhaustion. Heart period data was collected beat-by-beat with an RR-recorder (Polar Electro Ltd., Kempele, Finland) and VO_2 data breath-by-breath with a Vmax-analyzer (Sensor Medics, California, Palo Alto, USA).

Results

HR-based EPOC was found to correlate with measured EPOC and the goodness of fit (r^2) value was 0.79 (see Figure 7). Mean absolute error (MAE) values for the HR-based EPOC, when compared to the measured EPOC values, were 9.4, 14.0 and 16.9 ml/kg for 40% and 70% constant load exercise and for maximal incremental exercise, respectively. For the pooled data, MAE was 13.7 ml/kg. HR-based EPOC was also tightly connected with blood lactate levels, with the r^2-value being 0.79 (see Figure 8).

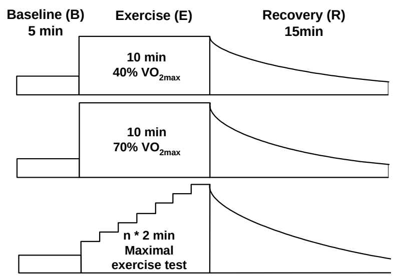

Figure 6. Submaximal and maximal exercise protocols on a cycle ergometer.

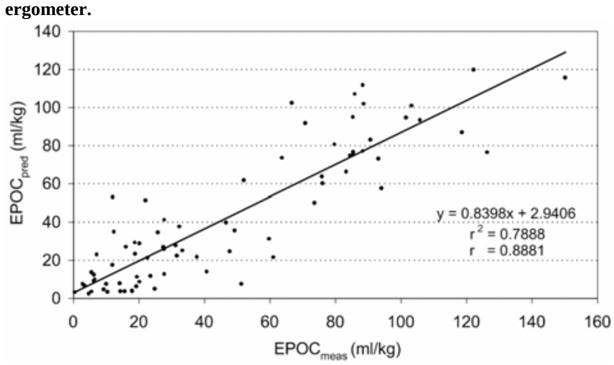

Figure 7. The correlation of heart beat derived EPOC (EPOC$_{pred}$) with measured EPOC (EPOC$_{meas}$) during cycle ergometry exercise. (Modified from Rusko et al. 2003)

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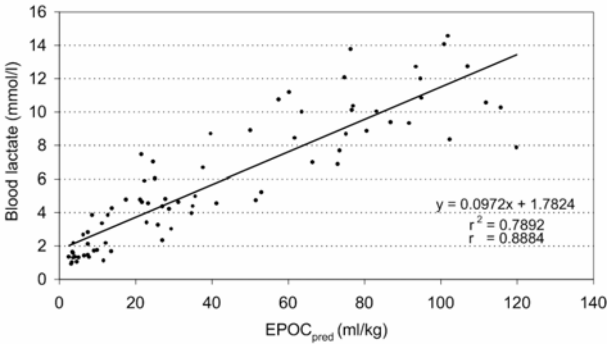

Figure 8. The correlation of HR-based EPOC ($EPOC_{pred}$) with blood lactate levels (Bla) during cycle ergometry exercise. (Modified from Rusko et al. 2003)

EPOC: ESSENTIAL INFORMATION ON EXERCISE

Table 1 summarizes the properties of exercise that determine the magnitude of EPOC. During exercise, EPOC increases or decreases depending on whether disturbance or recovery in homeostasis is expected. EPOC starts to decrease if the intensity decreases enough during exercise. This implies that the physiological training load is not increasing further, but is decreasing instead.

High EPOC-values are typically attained in exercise where cardiorespiratory load and oxygen consumption remain at high level without possibility to recover. Exercise that recruits large muscle mass, such as cross-country skiing and running, results in higher EPOC values than exercise that recruits small muscle mass. High EPOC values are also gained in intermittent exercise, such as interval training, soccer or squash, if recovery periods are short and intensity remains moderate. When applied to same exercise type, EPOC can be used to compare the demand of different exercises.

EPOC reflects mainly aerobic properties of the exercise and therefore, does not reflect optimally exhaustion due to local muscular fatigue and/or acidity. Thus, in strength exercise, EPOC may be low although the individual would be exhausted.

The day-to-day variation in the physiological training state of an individual can be tracked with EPOC. Short-term changes in performance, environmental factors and possible illnesses affect EPOC accumulation. EPOC is a sensitive measure for both cardiac and respiratory responses. Even slightly unusual responses can be tracked (see Table 2).

Table 1. EPOC depends on exercise properties.

Higher EPOC	Lower EPOC
Increased intensity	Decreased intensity
Longer duration	Shorter duration
Continuous exercise	Discontinuous exercise
Shorter recovery periods during intermittent exercise	Longer recovery periods during intermittent exercise
Active recovery during intermittent exercise	Passive recovery during intermittent exercise
Whole body exercise	Lower/upper body exercise

Table 2. Factors causing higher or lower HR-based EPOC values when compared to usual values.

EPOC is higher than usual	
Possible cause	**Recommended action**
Decreased fitness level.	Continue training. If possible, reduce the EPOC level back to normal or slightly below it.
Environmental conditions: increased altitude, temperature or humidity.	Decrease absolute work rate to match previous EPOC levels.
Not fully recovered from previous exercise.	Decrease training load and maximize recovery.
Illness.	Do not exercise if you suffer from an illness.
EPOC is lower than usual	
Possible cause	**Recommended action**
Recent monotonous, high-volume training period.	Assure recovery in your training program. Schedule both high- and low-intensity exercise into your training program.
Increased fitness level.	Increase intensity and/or duration of training to reach or slightly exceed former EPOC levels.

APPLICATIONS OF EPOC IN TRAINING

Controlling the training load during a single exercise session

EPOC can be applied across sports, as can be seen from Table 4. An individual willing to improve his/her fitness level can try different sports and check which ones are the best for his/her purpose.

EPOC can be used to confirm whether exercise fulfilled the purpose set before the exercise session. Table 3 represents the main types of aerobic exercise and the expected EPOC response. If the purpose is to enhance maximal aerobic fitness, EPOC should be high (see Figures 9 A and B). During low-intensity basic endurance exercise and separate warm-up exercises, EPOC should be kept at a low level. During cool-down, a decline in EPOC should be seen, indicating active recovery after exercise.

EPOC is useful in monitoring day-to-day changes in the physiological response to training. If there is an unexpected EPOC response, the training program can be adjusted depending on the cause of the different response. See Table 2.
EPOC reflects changes in fitness level. If peak EPOC is lower during the same exercise with the same workload (control exercise), the fitness level has probably improved because the disturbance of homeostasis is lower. Similarly, if EPOC is higher, the fitness level has most likely decreased. See Table 2 for additional explanations for higher or lower EPOC levels than usual. More fit individuals are able to exercise at the same relative intensity for a longer period of time than less fit individuals, which leads to higher EPOC.

Table 3. Summary of different types of targeted exercises and the related EPOC.

Exercise type and purpose	Exercise characteristics	Expected EPOC-response
Recovery exercise: To speed up lactate removal after exercise and cycle metabolic by-products in muscles.	Constant workload low-intensity exercise (30-50%VO_{2max}) of short duration (15 to 30 min). Blood lactate (Bla) levels remain at resting level or decrease towards the resting level. No disturbance or recovery of body's homeostasis.	EPOC remains at low level or decreases.
Basic endurance/slow distance training: To enhance the oxidation of fat and build up the endurance base (aerobic threshold).	Constant workload low-intensity exercise (40-60%VO_{2max}) of long duration (1 to several hours). Bla remains at resting level. No significant disturbance in body's homeostasis.	Slow accumulation of EPOC and a low EPOC peak.
Pace endurance/fast distance training: To enhance the oxidation of carbohydrates and lactate clearance (anaerobic threshold).	Constant workload exercise (60-85%VO_{2max}) of moderate to long duration (30 min to 1 hour). Bla increases above resting level. Significant disturbance of body's homeostasis.	Rapid accumulation of EPOC and a high EPOC peak.
VO_{2max} training: To improve maximal cardiorespiratory performance (VO_{2max}): oxidation of carbohydrates, lactate tolerance and fast force production (specific to race pace) of skeletal muscles.	Constant load or interval exercise with high intensity (>85%VO_{2max}), short to moderate duration (15 to 30 min). Bla increases rapidly and fatigue emerges quickly.	Very rapid accumulation of EPOC and a high to very high EPOC peak.

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When coaching a team, it is important to get information on the physiological responses of each individual. Team training sessions and games have a different impact on each player due to individual differences in e.g. fitness level, position, game style and motivation. With EPOC, the training load of each individual player can be monitored and the training program adjusted (e.g. some players may need more intense training while others need more rest after the games). See Figures 9 C and 9 D for an example in soccer.

Programming and periodization of training

The overall load that accumulates during training periods can also be evaluated with EPOC. A schematic example of training load over a training period of an endurance athlete is presented in Figure 10. The integration of training intensity and duration enables easier quantitative analysis of training. More accurate analysis of previous training loads helps in determining recovery requirements and designing subsequent training sessions optimally: the training load can be increased if the previous load is considered to have been too low, or decreased if the load had been higher than planned.

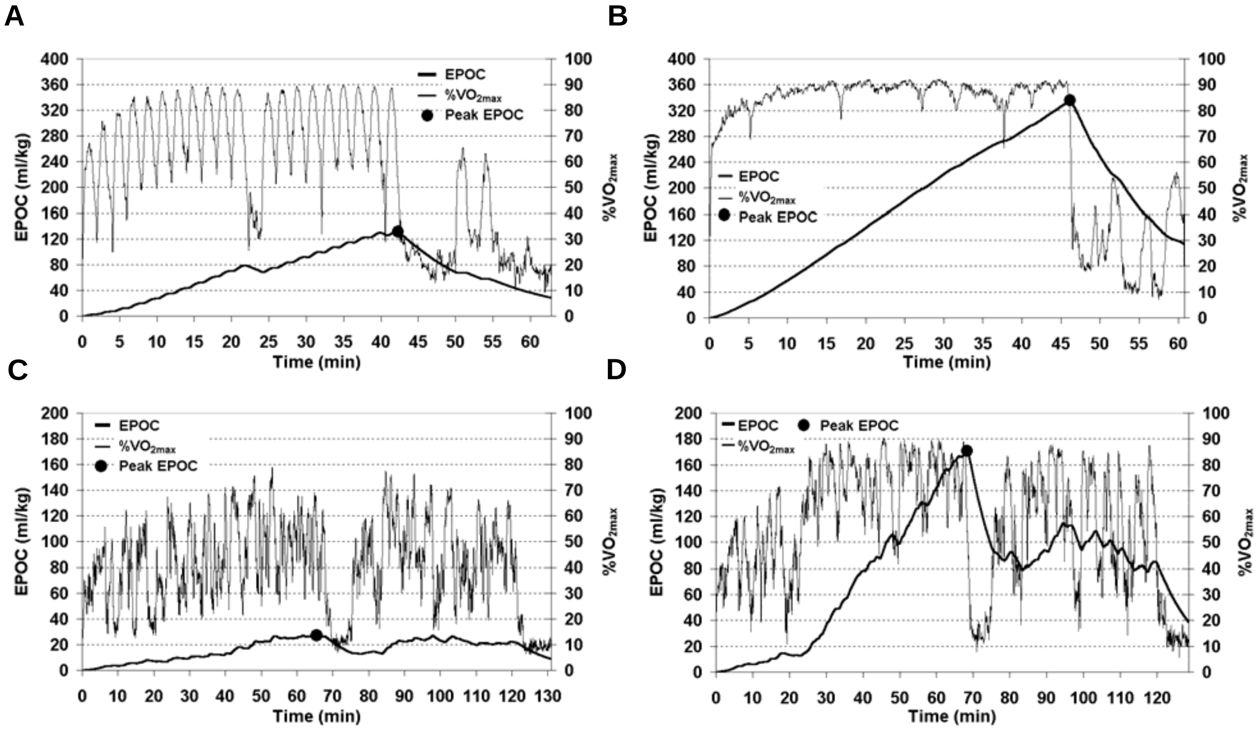

Figure 9. Examples of the accumulation of HR-based EPOC in different exercise sessions: (A) High-intensity interval training session (Nordic walking/running in a steep uphill). (B) High-intensity constant velocity running exercise. (C) A soccer player (defense) from the Finnish national league during a pre-season practice match. (D) A player from the same team (mid-fielder) in the same match. Note the difference in physiological load between the two players. The match was preceded by a 20-min warm-up and there was a half-time of about 10 min between the two halves.

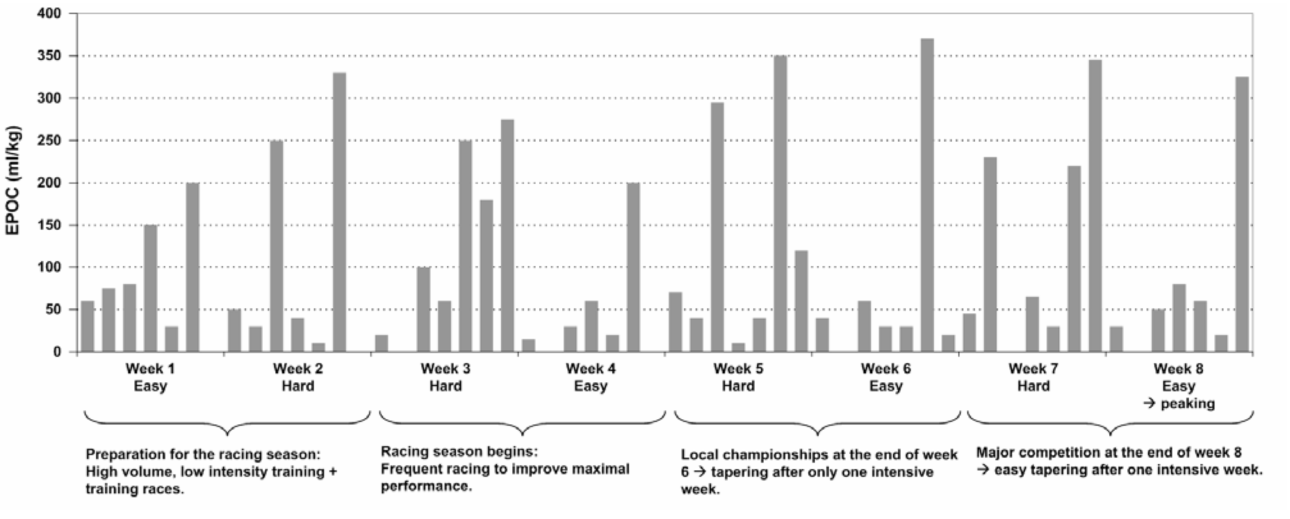

Figure 10. A schematic representation of an endurance athlete's training load during eight successive weeks (the columns represent daily values of EPOC). This two-month period prepares the athlete for the most important races of the season. The daily values are highest during weekends mainly due to races. Note also the less loading days before race days.

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Table 4. Accumulation of HR-based EPOC values in different sports.

Sport/activity	Typical exercise	Impact on maximal aerobic fitness (VO_{2max})	Typical EPOC (ml/kg)
Running	10-km race (27-50 min, 70-90% VO_{2max})	High – Very high	120-260
	Marathon 42 km (2h 10min - 5h, 65-85%VO_{2max})	High – Very high	120-650
	60 min low intensity (55-65%VO_{2max})	Low – Moderate	40-90
Walking	Brisk walk 1h (40-50 %VO_{2max})	Low	10-25
	Trekking with a backpack in hilly terrain for 5h (50-60% VO_{2max})	Low – Moderate	25-75
Cycling	Spinning session 40 min (60-80%VO_{2max})	Moderate – Very high	50-200
	Cycling to work 20 min (30-50%VO_{2max})	Low	5-15
Rowing	Aerobic workout with ergometer 30 min (65-75%VO_{2max})	Moderate – High	60-120
	Warm-up at gym with ergometer 10 min (55-65%VO_{2max})	Low	15-25
Cross-Country Skiing	15-km race (35-60min, 70-85%VO_{2max})	High – Very high	130-320
	90-km race (e.g. Vasaloppet: 3h 40 min-10 h, 50-80% VO_{2max})	Low – Very high	30-550
	2h low intensity (40-60% VO_{2max})	Low – Moderate	10-70
Soccer	Game 90 min, position: back	Low – High	30-150
	Game 90 min, position: mid-fielder, offence	High – Very high	150-300
Aerobics	45 min aerobics class (65-85 %VO_{2max})	Moderate – Very high	70-200
Badminton, Squash	1h game (70-80 %VO_{2max})	High – Very high	130-280
Tennis	1h game (50 -70% VO_{2max})	Low – High	25-130
Golf	Playing 18 holes (about 3 hours, 30-40% VO_{2max})	Very low – Low	5-10

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