Aerobic High-Intensity Intervals Improve $\dot{V}O_{2max}$ More Than Moderate Training

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[1]Department of Circulation and Imaging, Faculty of Medicine, Norwegian University of Science and Technology, Trondheim, NORWAY; [2]Hokksund Medical Rehabilitation Centre, Hokksund, NORWAY; [3]Department of Physical Medicine and Rehabilitation, St. Olav's University Hospital, Trondheim, NORWAY

ABSTRACT

HELGERUD, J., K. HØYDAL, E. WANG, T. KARLSEN, P. BERG, M. BJERKAAS, T. SIMONSEN, C. HELGESEN, N. HJORTH, R. BACH, and J. HOFF. Aerobic High-Intensity Intervals Improve $\dot{V}O_{2max}$ More Than Moderate Training. *Med. Sci. Sports Exerc.*, Vol. 39, No. 4, pp. 665–671, 2007. **Purpose:** The present study compared the effects of aerobic endurance training at different intensities and with different methods matched for total work and frequency. Responses in maximal oxygen uptake ($\dot{V}O_{2max}$), stroke volume of the heart (SV), blood volume, lactate threshold (LT), and running economy (C_R) were examined. **Methods:** Forty healthy, nonsmoking, moderately trained male subjects were randomly assigned to one of four groups:1) long slow distance (70% maximal heart rate; HR_{max}); 2) lactate threshold (85% HR_{max}); 3) 15/15 interval running (15 s of running at 90–95% HR_{max} followed by 15 s of active resting at 70% HR_{max}); and 4) 4 × 4 min of interval running (4 min of running at 90–95% HR_{max} followed by 3 min of active resting at 70% HR_{max}). All four training protocols resulted in similar total oxygen consumption and were performed 3 d·wk^{-1} for 8 wk. **Results:** High-intensity aerobic interval training resulted in significantly increased $\dot{V}O_{2max}$ compared with long slow distance and lactate-threshold training intensities ($P < 0.01$). The percentage increases for the 15/15 and 4 × 4 min groups were 5.5 and 7.2%, respectively, reflecting increases in $\dot{V}O_{2max}$ from 60.5 to 64.4 mL·kg^{-1}·min^{-1} and 55.5 to 60.4 mL·kg^{-1}·min^{-1}. SV increased significantly by approximately 10% after interval training ($P < 0.05$). **Conclusions**: High–aerobic intensity endurance interval training is significantly more effective than performing the same total work at either lactate threshold or at 70% HR_{max}, in improving $\dot{V}O_{2max}$. The changes in $\dot{V}O_{2max}$ correspond with changes in SV, indicating a close link between the two. **Key Words:** LACTATE THRESHOLD, AEROBIC POWER, 4 × 4-MIN INTERVALS, 15/15 TRAINING, STROKE VOLUME, BLOOD VOLUME

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It is important to know how different training intensities influence adaptations in physiological parameters when selecting an optimum training regimen for a specific sport or for improving fitness in the general community. Cardiorespiratory endurance has long been recognized as one of the fundamental components of physical fitness (1). Because accumulation of lactic acid is associated with skeletal muscle fatigue, anaerobic metabolism cannot contribute at a quantitatively significant level to the energy expended (1). Pate and Kriska (17) have described a model that incorporates the three major factors accounting for interindividual variance in aerobic endurance performance: maximal oxygen uptake ($\dot{V}O_{2max}$), lactate threshold (LT), and work economy (C). Several published studies support this model (3,5,8,12). Thus, the model should serve as a useful framework for comprehensive examination of the effects of aerobic training on endurance performance.

$\dot{V}O_{2max}$ is probably the single most important factor determining success in an aerobic endurance sport (1,20). However, within the same person, peak oxygen uptake is specific to a given type of activity. Therefore, to obtain relevant values, emphasis is placed on testing in activity-specific modes, such as walking and running, and in sport-specific activities for participants (24). At maximal exercise, the majority of evidence points to a $\dot{V}O_{2max}$ that is limited by oxygen supply, and cardiac output (Q) seems to be the major factor in determining oxygen delivery (28). In most textbooks, stroke volume of the heart (SV) and heart frequency are described as increasing linearly during upright increased work rates until about 50% of $\dot{V}O_{2max}$, where SV reaches a plateau or increases only modestly in both trained and sedentary subjects (11). However, other studies have shown that SV continues to increase beyond that rate. Zhou et al. (30) found that SV

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increased continuously with increased workload up to $\dot{V}O_{2max}$ in well-trained subjects. However, in sedentary and moderately trained subjects, the classical leveling off was found.

LT is the intensity of work or $\dot{V}O_2$ at which the blood lactate concentration gradually starts to increase during continuous exercise (5). Because LT reflects an onset of anaerobic metabolism and the coinciding metabolic alterations, this in turn determines the fraction of maximal aerobic power that can be sustained for an extended period (18). The blood lactate level ($[La^-]_b$) represents a balance between lactate production and removal, and there are individual patterns in these kinetics (2). LT changes in response to training with the alteration of $\dot{V}O_{2max}$ and sometimes also as the percentage of $\dot{V}O_{2max}$ (9,15,17).

Work economy, or C, is referred to as the ratio between work output and oxygen cost. Bunc and Heller (3), Helgerud (8), and Helgerud et al. (9) have shown the individual variations in gross oxygen cost of activity at a standard running velocity (C_R). A number of physiological and biomechanical factors seem to influence C_R in trained or elite runners. These include metabolic adaptations within the muscle such as increased mitochondria and oxidative enzymes, the ability of the muscles to store and release elastic energy by increasing the stiffness of the muscles, and more efficient mechanics leading to less energy wasted on braking forces and excessive vertical oscillation (17). Work economy also is improved from increased maximal strength and especially from improvements in rate of force development (12). Running economy is commonly defined as the steady-rate $\dot{V}O_2$ in milliliters per kilogram per minute at a standard velocity or as energy cost of running per meter ($mL \cdot kg^{-0.75} \cdot m^{-1}$) (5,8).

Most authors focus on the effects on $\dot{V}O_{2max}$ when evaluating the response to endurance training. Pollock (18) has shown that improvement in $\dot{V}O_{2max}$ is directly related to intensity, duration, and frequency of training. The minimum training intensity for improvement in $\dot{V}O_{2max}$ and LT seems to be approximately 55–65% of maximal heart rate (HR_{max}) (1). It has been suggested that lower-intensity work of longer duration can give the same training effect as high-intensity, short-duration work in some subjects (18); however, Wenger and Bell (29) observed higher training responses at higher intensities.

There are few studies where training protocols of different intensities have been matched for total work and frequency. Overend et al. (16) concluded that interval training (80% $\dot{V}O_{2max}$) offered no advantage over continuous training of the same average power output in altering the aerobic parameters in untrained adult males. However, Thomas et al. (27) have concluded that interval training (90% HR_{max}) may benefit aerobic capacity more so than continuous running (75% HR_{max}) in untrained men and women. This is in line with the conclusion of Rognmo et al. (19) that high-intensity aerobic interval exercise (80–90% $\dot{V}O_{2max}$) was superior to continuous low-intensity exercise (50–60% $\dot{V}O_{2max}$) in patients with coronary artery disease. The aim of this study is, thus, to compare training methods of different intensity matched for energy consumption. The hypothesis is that long slow distance running (LSD), that is, continuous work at 70% of HR_{max} and at LT level (85% HR_{max}), will show less training effects on $\dot{V}O_{2max}$ than a similar workload of short-interval (15 s of work and 15 s of active recovery) and long-interval (4 × 4 min, 3 min of active recovery) aerobic endurance training at 90–95% HR_{max}.

METHODS

Subjects. Fifty-five healthy, nonsmoking male university students were recruited for participation in the study. All subjects were engaged in endurance training and leisure-time physical activity at least three times per week. Each subject reviewed and signed consent forms approved by the human research committee before participating in the study. All subjects were randomly assigned to one of four training groups. During the training period, 13 subjects dropped out of the study because of illness and injuries not related to the study. In addition, two of the subjects were excluded because they participated in fewer than 90% of the training sessions. The age, height, and weight of the 40 participating subjects were 24.6 ± 3.8 yr, 182 ± 6 cm, and 82.0 ± 12.0 kg, respectively. Because of difficulties in performing the procedures for single-breath acetylene uptake (SB) for measuring Q, four subjects in each group were not able to perform both pre and post measurements. As such, the Q and SV measurements include data from six subjects per group. The hematological responses were measured on a separate day. For reasons not related to the training, two subjects in the LSD training and one subject in the 4 × 4 min training group were not able to attend both pre- and postmeasuring sessions of hematological responses.

Test procedures and material. A Technogym Runrace (Italy) treadmill calibrated for inclination and speed, at an inclination of 5.3%, was used for all physical capacity measurements. The measurements of $\dot{V}O_{2max}$, lactate threshold, work economy, all ventilatory parameters, and pulmonary gas exchange were obtained using the Cortex Metamax II portable metabolic test system (Cortex Biophysik GmbH, Leipzig, Germany). Recently, Metamax II has been validated against the classic Douglas bag technique (14). Mean differences in $\dot{V}O_2$ (0.03, 0.02, and 0.04 $L \cdot min^{-1}$ for 100, 200, and 250 W, respectively), and pulmonary ventilation ($\dot{V}_E$; 1.6, 2.9, 1.5 $L \cdot min^{-1}$ for 100, 200, and 250 W, respectively) were small but significant for 100 W ($\dot{V}O_2$ and $\dot{V}_E$) and 200 W ($\dot{V}_E$). However, intraclass coefficients of correlation were high throughout. Bland–Altman plots revealed 95% limits of agreement of ± 0.2 $L \cdot min^{-1}$ for $\dot{V}O_2$ (bias 0.04 $L \cdot min^{-1}$) and slightly below ± 6 $L \cdot min^{-1}$ for $\dot{V}_E$ (bias 1.9 $L \cdot min^{-1}$).

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The subjects were familiarized with treadmill running (45 min) twice before the start of the study. The test started with a warm-up period of 10 min at approximately 60% of predicted $\dot{V}O_{2max}$, before establishing a baseline value of blood lactate concentration $[La^-]_b$. To determine LT, the subjects ran a maximum of five increasing intensities for 5 min at 60–95% $\dot{V}O_{2max}$, with a 30-s break for the determination of $[La^-]_b$ from a fingertip. For all subjects, this included one 4-min step at 7 $km \cdot h^{-1}$ at 5.3% inclination for the determination of running economy at this standardized workload. The running speeds used to determine LT were exactly the same for a given subject in the pre- and the posttraining tests. Lactate measurements were made using a YSI 1500 Sport Lactate Analyzer (Yellow Springs Instruments, Yellow Springs, OH). LT was calculated as the velocity or $\dot{V}O_2$ that corresponded with $[La^-]_b$ 1.5 mmol higher than the warm-up values (10). As soon as $[La^-]_b$ was 1.5 mmol higher than warm-up values, the subjects proceeded to the $\dot{V}O_{2max}$-testing protocol. For the measurement of $\dot{V}O_{2max}$, the speed was increased every minute to a level that brought the subject to exhaustion in 3–6 min. Achievement of $\dot{V}O_{2max}$ was accepted when $\dot{V}O_2$ leveled off despite further increases in running speed and when a respiratory exchange ratio (R) above 1.05 was present. The highest heart rate during the last minute was measured and used as HR_{max}. For assessing HR, Polar Accurex heart rate monitors were used (Polar Electro, Finland). Q and SV were measured 2 d after the LT and $\dot{V}O_{2max}$ tests using a Sensormedics Vmax Spectra 229 apparatus. Before the test, the subjects started a 10-min warm-up period at 70% of HR_{max} that included multiple training bouts for the procedures for single-breath acetylene uptake (SB). The testing procedure started by gradually increasing velocity to the speed corresponding to $\dot{V}O_{2max}$ at the maximal test (i.e., maximal aerobic velocity). When the subjects were close to their $\dot{V}O_{2max}$, they were instructed to start the breathing cycle when they were ready. The Q measurement procedure started with a complete emptying of the lungs and then maximal inspiration of a gaseous mixture of 0.3% carbon monoxide (CO), 0.3% methane (CH_4), 0.3% acetylene (C_2H_2), 21% oxygen (O_2), and 80% nitrogen (N_2), directly followed by one continuous expiration. The SB has been validated with the indirect Fick CO_2-rebreathing method and compared with open-circuit acetylene uptake (4). Both techniques were shown to be valid and reliable for measuring Q. Repeated measurements of Q were made using the SB at rest, 100 W, and 200 W. There were no significant differences between repeated measures of this technique at any workload. The standard error of measurement decreased with increasing intensity and was 8.5% at rest and 3.2% at 200 W. Standard error (absolute) was similar at all levels of intensity, ranging from 0.47 to 0.56 $L \cdot min^{-1}$. The coefficient of variation (CV) was 7.6% at 200 W. However, the authors concluded that the SB, requiring a constant, slow exhalation rate, made the procedure difficult to perform at the highest exercise intensities (4).

Hematological measurements. In two of the training groups, the LSD and 4 × 4 min groups, blood volume was measured by determining the concentration of Evans blue dye in blood sampled at 10, 20, and 30 min after injection of approximately 2.5 mL of 1.5% Evans blue dye. Blood samples were centrifuged at 3500 rpm for 10 min in an ultracentrifuge (Kubota 2010, Japan). Blood plasma was analyzed for blue dye concentration using a spectrophotometer (Shimadzu UV-1601, Japan) at wavelengths of 620 and 740 nm. Hematocrit was analyzed using a Cobas Micros CT16 (Bergman Instrumentering AS, Norway).

Training interventions. The present study consists of four training interventions. To equate the total amount of work for each of the training sessions, a thorough calculation was carried out.

1. Long slow distance running (LSD): The first group performed a continuous run at 70% HR_{max} (137 ± 7 bpm) for 45 min.
2. Lactate threshold running (LT): The second group performed a continuous run at lactate threshold (85% HR_{max}, 171 ± 10 bpm) for 24.25 min.
3. 15/15 interval running (15/15): The third group performed 47 repetitions of 15-s intervals at 90–95% HR_{max} (180 to 190 ± 6 bpm) with 15 s of active resting periods at warm-up velocity, corresponding to 70% HR_{max} (140 ± 6 bpm) between.
4. 4 × 4-min interval running (4 × 4 min): A fourth group trained 4 × 4-min interval training at 90–95% HR_{max} (180 to 190 ± 5 bpm) with 3 min of active resting periods at 70% HR_{max} (140 ± 6 bpm) between each interval.

Training interventions 2–4 started with a 10-min warm-up and ended with a 3-min cool-down period at 70% HR_{max}. All training sessions were performed running on a treadmill at 5.3% inclination (Fig. 1).

The calculation of the total oxygen uptake for the different training protocols was based on the relationship between $\%HR_{max}$ and $\%\dot{V}O_{2max}$ established by the American College of Sports Medicine (ACSM) (26). ACSM states that 70, 85, and 92.5% HR_{max} can be used as indices for 60, 80, and 87.5% of $\dot{V}O_{2max}$. A pilot study was performed to assure that the total oxygen cost required for each training regimen was the same—warm-up, active recovery, and cool-down periods included. Eight nonsmoking male subjects participated in the pilot study (age 26.2 ± 3.3 yr, height 180.5 ± 6.8 cm, weight 82.1 ± 11.5 kg). $\dot{V}O_{2max}$ was 4.80 ± 0.49 $L \cdot min^{-1}$ and 58.5 ± 5.9 $mL \cdot kg^{-1} \cdot min^{-1}$. HR_{max} was 202 ± 12 bpm. All subjects performed all four training protocols with at least 1 d of rest in between. The results showed no significant difference between the measured values for total oxygen uptake in any of the protocols performed. Expressed as a percentage of the mean $\dot{V}O_2$ expenditure, the coefficient of repeatability (COR) was 11.9%. On average, the

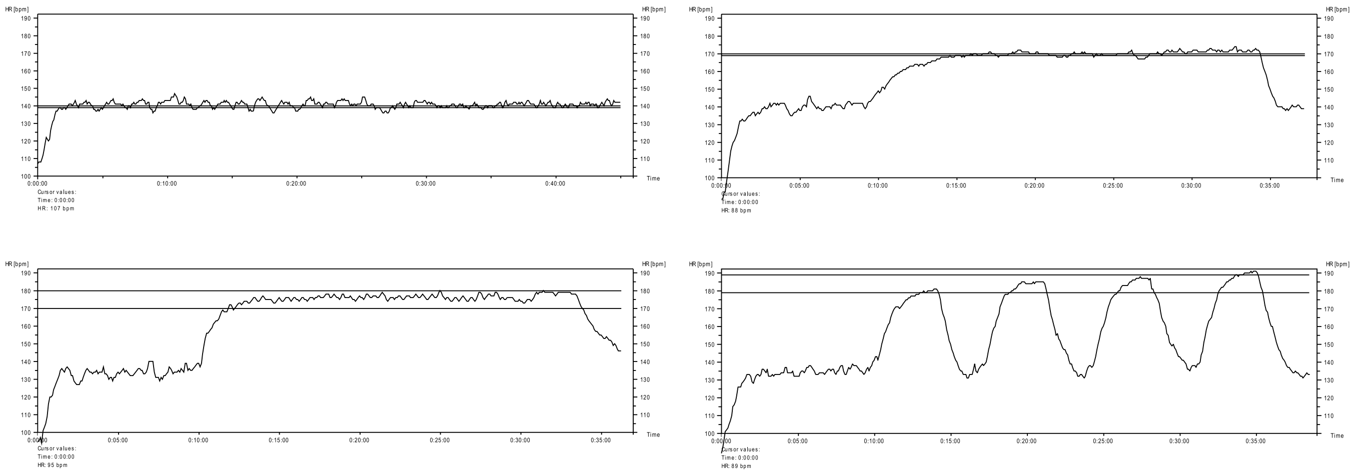

FIGURE 1—Examples of the heart rate response to the four different training regimens in a subject from each group. Subject a (HR_{max} 200 bpm); long slow distance running (LSD) 70% HR_{max}. Subject b (HR_{max} 200 bpm): lactate threshold running (LT), 85% HR_{max}. Subject c (HR_{max} 189 bpm): 15-s interval running at 90–95% HR_{max}, with 15 s of active recovery (15/15). Subject d (HR_{max} 199 bpm): 4 × 4-min interval running at 90–95%, with 3 min of active recovery (4 × 4 min).

measured total oxygen uptake for the training protocols were LSD: 131.0 ± 12.9 L; LT: 128.1 ± 10.5 L; 15/15: 133.6 ± 16.0 L; 4 × 4 min: 127.3 ± 14.6 L. When the heart rate started to increase (drift) in the LSD and LT group, the speed of the treadmill was reduced to secure the target intensity. In the 15/15 group, the subjects were instructed to reach the target intensity in about 3–4 min and then adjust the speed to stay there. In the 4 × 4 min group, the subjects were instructed to reach the target intensity in about 1–1.5 min and then stay there by adjusting the speed of the treadmill. The total distance covered (including active recovery periods) in each training bout for each group at pretraining was, on average, 5.9 km. The subjects carried out three training sessions per week for 8 wk.

Statistical analysis. Statistical analyses were performed using the software program SPSS, version 11.0 (Statistical Package for Social Science, Chicago, IL). In all cases, $P < 0.05$ were taken as the level of significance in two-tailed tests. The results are presented as mean ± SD and mean ± SE in Figure 2. To calculate differences between and within groups, a two-way analysis of repeated-measures ANOVA (least significance difference test) were used for comparison of means for continuous variables. The data were tested for normal distribution using quantile–quantile (QQ) plots. The results of the QQ plots were interpreted by examining the shape of the plots and the closeness of the plot to its best linear fit.

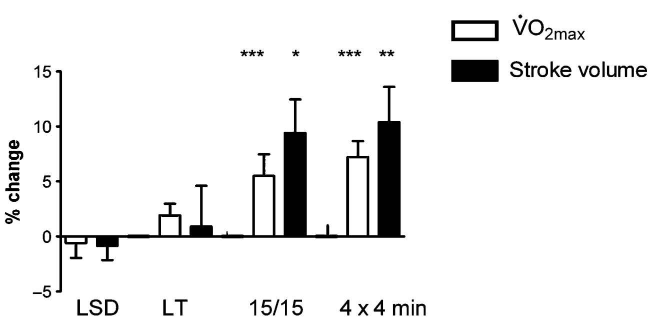

FIGURE 2—Percent change in absolute $\dot{V}O_{2max}$ ($L{\cdot}min^{-1}$) and absolute stroke volume of the heart ($mL{\cdot}beat^{-1}$) from pre- to posttraining for each of the groups, presented as mean and SE. Significantly different from pre- to posttraining: * $P < 0.05$, ** $P < 0.01$, *** = $P < 0.001$.

RESULTS

The high–aerobic intensity training performed by the 15/15 and 4 × 4 min groups increased absolute $\dot{V}O_{2max}$ ($L{\cdot}min^{-1}$) significantly compared with LSD and LT training. Between the 15/15 and the 4 × 4 min groups, no significant difference in training response was observed. $\dot{V}O_{2max}$ increased from pre- to posttraining in both the 15/15 (5.5%) and 4 × 4 min (7.2%) groups, but no change was apparent in the LT or LSD group (Table 1, Fig. 2). Running economy (C_R) was not significantly different between groups (Table 1), but all of the training groups significantly improved their running economy, ranging from 7.5 to 11.7%. LT did not change for any group when expressed as %$\dot{V}O_{2max}$. The velocity at LT (vLT) was, however, significantly improved by an average of 9.6% in all four groups as a consequence of changes in running economy and $\dot{V}O_{2max}$.

SV changed significantly from pre- to posttraining for the 15/15 and 4 × 4 min group (Table 2). No between-group differences were observed. The highest average SV was 0.16 $L{\cdot}beat^{-1}$, and the highest average Q was 32.6 $L{\cdot}min^{-1}$ at posttraining. Oxygen uptake at the maximal aerobic velocity at which SV and Q were measured was, on average, 7.2% lower than when tested during the $\dot{V}O_{2max}$ protocol. Similarly lower ventilations

TABLE 1. Changes in physiological parameters from pre- to posttraining.

	LSD (N = 10)		LT (N = 10)		15/15 (N = 10)		4 × 4 min (N = 10)	
	Pretraining	Posttraining	Pretraining	Posttraining	Pretraining	Posttraining	Pretraining	Posttraining
$\dot{V}O_{2max}$								
($L \cdot min^{-1}$)	4.77 ± 0.49	4.74 ± 0.46	4.58 ± 0.38	4.67 ± 0.40	4.91 ± 0.60	5.18 ± 0.56***#[a]	4.56 ± 0.62	4.89 ± 0.52***#[b]
($mL \cdot kg^{-1} \cdot min^{-1}$)	55.8 ± 6.6	56.8 ± 6.3	59.6 ± 7.6	60.8 ± 7.1	60.5 ± 5.4	64.4 ± 4.4**#[a]	55.5 ± 7.4	60.4 ± 7.3***#[b]
($mL \cdot kg^{-0.75} \cdot min^{-1}$)	169.4 ± 17.5	171.6 ± 17.0	176.1 ± 18.0	179.5 ± 16.6	183.1 ± 16.4	194.7 ± 14.7**#[a]	167.0 ± 19.9	181.7 ± 19.1***#[b]
HR_{max} (bpm)	196 ± 7	195 ± 8	201 ± 10	198 ± 9	200 ± 6	199 ± 4	199 ± 8	197 ± 7
$\dot{V}_E$ ($L \cdot min^{-1}$)	150.6 ± 15.0	155.0 ± 17.8	148.8 ± 17.4	153.6 ± 15.9	147.5 ± 13.2	160.3 ± 14.2	150.7 ± 17.6	164.8 ± 18.1
R	1.10 ± 0.04	1.10 ± 0.05	1.10 ± 0.05	1.10 ± 0.05	1.09 ± 0.05	1.12 ± 0.04	1.10 ± 0.05	1.12 ± 0.04
$[La^-]_b$	8.57 ± 1.61	7.63 ± 1.04	7.72 ± 0.82	7.43 ± 0.84	9.50 ± 1.90	8.40 ± 0.80	8.50 ± 1.14	8.84 ± 0.94
Running economy								
$\dot{V}O_2$ ($mL \cdot kg^{-0.75} \cdot m^{-1}$)	0.80 ± 0.09	0.74 ± 0.08*	0.85 ± 0.09	0.75 ± 0.09***	0.79 ± 0.06	0.73 ± 0.07*	0.79 ± 0.06	0.71 ± 0.05**
HR (bpm)	150 ± 17	140 ± 9**	151 ± 15	137 ± 10***	147 ± 16	125 ± 9**	154 ± 22	136 ± 17***
Lactate threshold								
$\dot{V}O_2$ ($L \cdot min^{-1}$)	3.55 ± 0.50	3.52 ± 0.50	3.54 ± 0.49	3.51 ± 0.50	3.96 ± 0.54	3.99 ± 0.56	3.73 ± 0.46	3.76 ± 0.43
$\%\dot{V}O_{2max}$	74.4 ± 3.1	74.3 ± 5.7	77.2 ± 6.6	75.2 ± 5.5	80.6 ± 5.6	77.3 ± 2.8	78.6 ± 8.5	76.9 ± 4.5
$\%HR_{max}$	87.1 ± 3.2	86.5 ± 5.4	84.7 ± 4.3	84.3 ± 3.7	89.7 ± 2.8	87.0 ± 2.9	88.8 ± 7.6	85.8 ± 4.1
vLT ($km \cdot h^{-1}$)	9.7 ± 1.2	10.5 ± 1.2**	9.5 ± 1.6	10.6 ± 1.8**	11.2 ± 0.6	12.3 ± 0.8**	10.3 ± 2.3	11.2 ± 1.9**
$[La^-]_b$ (mM)	2.75 ± 0.62	2.41 ± 0.24	2.94 ± 0.49	2.46 ± 0.31	3.30 ± 1.20	2.70 ± 0.50	2.57 ± 0.42	2.50 ± 0.44
Mass (kg)	86.2 ± 9.1	83.9 ± 7.6*	78.2 ± 13.1	77.8 ± 12.7	80.6 ± 10.7	79.8 ± 9.7	82.9 ± 13.0	81.4 ± 11.84

Data are presented as means ± SD. The test was carried out running on a treadmill at 5.3% inclination. LSD, long slow distance running; LT, lactate threshold; $\dot{V}O_2$, oxygen uptake; HR_{max}, maximal heart rate; $\dot{V}_E$, pulmonary ventilation; $[La^-]_b$, blood lactate concentration after $\dot{V}O_{2max}$ testing; R, respiratory exchange ratio; vLT, velocity at lactate threshold. * Significant differences ($P < 0.05$) within groups from pre- to posttraining; ** significant difference ($P < 0.01$) within groups from pre- to posttraining; *** significant difference within groups ($P < 0.001$) from pre- to posttraining; # significant difference between groups from pre- to posttraining. [a] 15/15 vs LSD and LT is significant at $P < 0.001$ and $P < 0.05$, respectively. [b] The difference between 4 × 4 min vs the LSD and LT is significant at $P < 0.001$ and $P < 0.01$, respectively.

were measured when running at the calculated maximal aerobic velocity (Table 2). No significant changes took place in the hematological responses to training (Table 3). Blood volume was calculated to be, on average, 7.2% of subject body weight.

DISCUSSION

The major novel finding of this research is that high–aerobic intensity endurance training is significantly more effective than moderate- and low-intensity training in improving $\dot{V}O_{2max}$ during a training period of 8 wk. Up to the level of maximum aerobic velocity, the intensity of training determines the training response. Intensity and volume of training are, thus, not interchangeable. The changes in $\dot{V}O_{2max}$ correspond with changes in stroke volume of the heart (SV), indicating a close link between the two.

$\dot{V}O_{2max}$. $\dot{V}O_{2max}$ is one of the primary determinants of aerobic endurance performance (1). The high–aerobic intensity interval training regimens of 15/15 and the 4 × 4 min performed at the same intensity both revealed significantly higher absolute $\dot{V}O_{2max}$ responses of 5.5 and 7.3%, respectively, over the moderate- and lower-intensity training of the O_2 cost-matched LT and LSD training groups. The effect of interval training is in line with previous studies (7,13). It has been suggested a longer duration for training sessions could compensate for lower-intensity exercise (16,18). However, the present study, which matched four training protocols for total work and frequency, does not support this claim. Instead, our results are consistent with those of Wenger and Bell (29) and Thomas et al. (27), who found that intensity of training cannot be compensated for by longer duration.

Improvements in $\dot{V}O_{2max}$ seem to be dependent on fitness level. In a recent paper, we have shown an improvement in $\dot{V}O_{2max}$ of 7% for cardiovascular patients

TABLE 2. Changes in cardiac output and stroke volume from pre- to posttraining when running at the velocity of $\dot{V}O_{2max}$.

	LSD (N = 6)		LT (N = 6)		15/15 (N = 6)		4 × 4 min (N = 6)	
	Pretraining	Posttraining	Pretraining	Posttraining	Pretraining	Posttraining	Pretraining	Posttraining
SV ($mL \cdot kg^{-1} \cdot beat^{-1}$)	1.82 ± 0.22	1.86 ± 0.35	1.76 ± 0.23	1.78 ± 0.35	1.81 ± 0.31	1.99 ± 0.31*	1.76 ± 0.38	1.98 ± 0.45**
SV ($mL \cdot beat^{-1}$)	154.2 ± 19.8	152.9 ± 22.4	128.5 ± 16.9	129.7 ± 15.9	148.7 ± 18.3	162.7 ± 20.7*	144.2 ± 21.9	159.2 ± 21.9**
Q ($L \cdot min^{-1}$)	30.29 ± 4.50	30.05 ± 5.10	25.73 ± 2.06	26.00 ± 2.52	29.78 ± 3.32	32.59 ± 5.20*	28.45 ± 3.08	31.43 ± 2.50**
HR (bpm)	187 ± 11	185 ± 9	195 ± 6	194 ± 9	185 ± 9	182 ± 10	191 ± 12	186 ± 7
$\dot{V}O_2$								
($L \cdot min^{-1}$)	4.59 ± 0.60	4.48 ± 0.41	4.01 ± 0.13	4.20 ± 0.16	4.72 ± 0.63	4.99 ± 0.43*	4.39 ± 0.64	4.80 ± 0.51*
($mL \cdot kg^{-1} \cdot min^{-1}$)	53.4 ± 6.2	54.0 ± 6.1	53.4 ± 8.9	56.5 ± 9.8	55.7 ± 5.2	60.1 ± 3.5*	51.8 ± 7.3	54.8 ± 6.7*
($mL \cdot kg^{-0.75} \cdot min^{-1}$)	162.4 ± 17.3	162.8 ± 15.7	156.7 ± 19.6	166.8 ± 22.1	167.7 ± 14.6	180.9 ± 8.6*	156.8 ± 19.6	166.0 ± 16.9**
$\dot{V}_E$ ($L \cdot min^{-1}$)	134.1 ± 10.4	135.3 ± 15.5	111.7 ± 22.0	127.0 ± 18.0	103.6 ± 24.8	121.6 ± 24.8	133.5 ± 16.9	143.8 ± 10.3
R	1.09 ± 0.05	1.10 ± 0.05	1.03 ± 0.14	1.08 ± 0.07	1.07 ± 0.03	1.07 ± 0.05	1.09 ± 0.02	1.08 ± 0.03

Data are presented as means ± SD. The test was carried out running on a treadmill at 5.3% inclination. LSD, long slow distance running; LT, lactate threshold; Q_{max}, maximal cardiac output; SV_{max}, maximal stroke volume; $\dot{V}O_2$, oxygen uptake; HR_{max}, maximal heart rate; $\dot{V}_E$, pulmonary ventilation; R, respiratory exchange ratio. * Significant differences ($P < 0.05$) within groups from pre- to posttraining; ** significant difference ($P < 0.01$) within groups from pre- to posttraining.

TABLE 3. Hematological responses to low- and high-intensity aerobic training.

	LSD (N = 8)		4 × 4 min (N = 9)	
	Pretraining	Posttraining	Pretraining	Posttraining
Blood volume (L)	5.81 ± 0.83	6.14 ± 0.75	5.81 ± 0.84	5.95 ± 0.80
Blood volume (mL·kg^{-1})	65.67 ± 6.27	71.57 ± 7.37	73.56 ± 6.85	75.88 ± 10.75
Red cell mass (L)	2.17 ± 0.32	2.36 ± 0.33	2.30 ± 0.45	2.27 ± 0.38
Red cell mass (mL·kg^{-1})	24.58 ± 2.49	27.49 ± 2.97	26.53 ± 4.43	26.53 ± 4.43
Hemoglobin (g·dL^{-1})	14.73 ± 0.74	14.42 ± 0.46	14.60 ± 0.88	14.01 ± 1.15
Hematocrit (%)	43.1 ± 2.2	44.2 ± 1.9	43.5 ± 3.4	42.9 ± 3.6
Glucose (mM)	5.30 ± 0.56	5.14 ± 0.29	4.77 ± 0.39	4.84 ± 0.26
Triglycerides (mM)	0.94 ± 0.48	0.80 ± 0.24	1.04 ± 0.43	0.94 ± 0.61
HDL (mM)	1.18 ± 0.22	1.23 ± 0.23	1.32 ± 0.35	1.26 ± 0.31
LDL (mM)	2.86 ± 0.81	2.77 ± 0.95	2.84 ± 0.52	2.84 ± 0.50
CK (U·L^{-1})	206.1 ± 131.0	138.7 ± 52.2	161.5 ± 122.4	165.3 ± 96.6

Data are presented as means ± SD. LSD, long slow distance running; HDL, high-density lipoprotein; LDL, low-density lipoprotein; CK, creatine kinase.

using LSD training three times per week for 10 wk, whereas the work-matched 4 × 4-min interval training resulted in a 17.9% increase in $\dot{V}O_{2max}$ (19). Training responses of 5–10% have been shown using 4 × 4 min training interventions twice per week for professional youth soccer players (8) at a similar fitness level as in this experiment, whereas the control group of football players did not reveal any change. The lower improvement in $\dot{V}O_{2max}$ at higher fitness levels is in line with previous observations (20).

Stroke volume of the heart. Q is determined by SV and HR_{max}. Because HR_{max} does not change with training, changes in Q are determined by changes in SV. The SV in the high–aerobic intensity interval groups at posttraining in the present experiment were approximately 0.16 L·beat^{-1}, in line with what has been presented for highly trained endurance athletes (30). Q in this experiment for the 15/15 group and the 4 × 4 min group was approximately 30 L·min^{-1}. Using the single-breath technique of acetylene uptake (SB), the measurements are highly dependent on a subject's ability to perform the breathing task properly, which might be difficult when approaching intensity close to $\dot{V}O_{2max}$. The slightly lower $\dot{V}O_2$ and ventilation in the protocol for Q measurements indicate that the real maximal Q in this experiment might actually be somewhat higher. This experiment shows that improvements in $\dot{V}O_{2max}$ seem to be followed by similar improvements in SV, indicating a strong dependence between these parameters, in line with the hypothesis.

Blood volume and hematological responses. In this experiment, no significant change in blood volume was observed in the two groups examined. Red blood cell mass or hemoglobin did not increase for any of the groups, indicating no change in oxygen-carrying capacity with training. Thus, blood volume and oxygen-carrying capacity of the blood do not seem to explain the changes in $\dot{V}O_{2max}$ in this experiment. This is partly supported by the lack of change in cardiovascular function with acute plasma volume expansion in trained athletes (21).

Running economy. In the present study, all training groups significantly improved running economy (C_R) at 7 km·h^{-1}, 5.3% inclination, with no differences observed between the groups. The within-group comparison shows a significant improvement in C_R from pre- to posttraining of about 5%. Improved C_R is to be expected because of the large amount of running training carried out during the training program and because the subjects did not participate in any regular running training before the study. The present result is compatible with those from the study by Helgerud (8), who found that higher $\dot{V}O_{2max}$ in men versus performance-matched women is compensated for by superior C_R as a result of more running. Helgerud et al. (9) found that C_R was improved by 6.7% in an 8-wk running program of 4 × 4-min interval training compared with a control group that only participated in regular soccer training. Although this may be expected, the current study and previous research (5,8,9) suggest that C_R is not affected by the running speed used during training.

Lactate threshold. The present study found no significant change in LT in any training groups when expressed as %$\dot{V}O_{2max}$. Although commonly claimed (6), several studies have found no change in LT as %$\dot{V}O_{2max}$ previously (9,15,22,23). All groups significantly improved running velocity at LT (vLT); on average, 9.6%. However, because vLT follows the improvement in $\dot{V}O_{2max}$ (9,15), and because all groups improved C_R, higher vLT would be expected. Similar results regarding vLT have been found previously (25).

CONCLUSIONS

The present study has revealed that the 15/15 and the 4 × 4 min training groups of healthy students that trained at aerobic high intensity (i.e., 90–95% HR_{max}) increased their $\dot{V}O_{2max}$ significantly. However, the LSD and the LT groups training at 70 and 85% HR_{max} did not change their $\dot{V}O_{2max}$. The increases in $\dot{V}O_{2max}$ seem to be a function of increased SV resulting in increased Q. Training at LSD and LT did not change the SV. We conclude that when total work and training frequency are matched, higher aerobic intensity leads to larger improvements in $\dot{V}O_{2max}$. In all the training groups C_R improved significantly, with no differences between groups. We conclude, then, that C_R seems not to be velocity specific within the running intensities corresponding to 70–95% $\dot{V}O_{2max}$ for healthy subjects. There were no significant group differences in

LT when expressed as a percentage of $\dot{V}O_{2max}$. Although both the 15/15 training group and the 4 × 4 min training group improved $\dot{V}O_{2max}$, the 47 repetitions of 15 × 15 s training at a velocity that eventually gives a heart rate at 90–95% HR_{max} is difficult to administer. Interval training with longer intervals, like the 4 × 4 min training administered in this experiment, is thus recommended to improve $\dot{V}O_{2max}$.

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Aerobic High-Intensity Intervals Improve VË™ O2max More Than Moderate Training. Med. Sci. Sports Exerc., Vol. 39, No. 4, pp. 665â€“671, 2007. Purpose: The present study compared the effects of aerobic endurance training at different intensities and with different methods matched for total work and frequency.Â Results: High-intensity aerobic interval training resulted in significantly increased VË™ O2max compared with long slow distance and lactate-threshold training intensities (P G 0.01). The percentage increases for the 15/15 and 4 Ã, 4 min groups were 5.5 and 7.2%, respectively, reflecting increases in VË™ O2max from 60.5 to 64.4 mLIkgj1Iminj1 and 55.5 to 60.4 mLIkgj1Iminj1. SV increased significantly by approximately 10% after interval training (P G 0.05).