Effect of endurance training on oxygen uptake kinetics during treadmill running

HELEN CARTER1, ANDREW M. JONES,2 THOMAS J. BARSTOW,3 MARK BURNLEY,4 CRAIG WILLIAMS,4 AND JONATHAN H. DOUST1
1University of Surrey Roehampton, London SW15 3SN; 2Exercise Physiology Group, Manchester Metropolitan University, Alsager ST7 2HL, United Kingdom; 3Department of Kinesiology, Kansas State University, Manhattan, Kansas 66506-0302; and 4Chelsea School Research Centre, University of Brighton, Eastbourne BN20 7SP, United Kingdom

Received 1 September 1999; accepted in final form 8 June 2000

Carter, Helen, Andrew M. Jones, Thomas J. Barstow, Mark Burnley, Craig Williams, and Jonathan H. Doust. Effect of endurance training on oxygen uptake kinetics during treadmill running. J Appl Physiol 89: 1744–1752, 2000.—The purpose of this study was to examine the effect of endurance training on oxygen uptake (V˙O2) kinetics during moderate [below the lactate threshold (LT)] and heavy (above LT) treadmill running. Twenty-three healthy physical education students undertook 6 wk of endurance training that involved continuous and interval running training 3–5 days per week for 20–30 min per session. Before and after the training program, the subjects performed an incremental treadmill test to exhaustion for determination of the LT and the V˙O2 max and a series of 6-min square-wave transitions from rest to running speeds calculated to require 80% of the LT and 50% of the difference between LT and maximal V˙O2. The training program caused small (3–4%) but significant increases in LT and maximal V˙O2 (P < 0.05). The V˙O2 kinetics for moderate exercise were not significantly affected by training. For heavy exercise, the time constant and amplitude of the fast component were not significantly affected by training, but the amplitude of the V˙O2 slow component was significantly reduced from 321 ± 32 to 217 ± 23 ml/min (P < 0.05). The reduction in the slow component was not significantly correlated to the reduction in blood lactate concentration (r = 0.39). Although the reduction in the slow component was significantly related to the reduction in minute ventilation (r = 0.46; P < 0.05), it was calculated that only 9–14% of the slow component could be attributed to the change in minute ventilation. We conclude that the V˙O2 slow component during treadmill running can be attenuated with a short-term program of endurance running training.

The physiological mechanism(s) responsible for this slow-component rise in V˙O2 with time during supra-LT exercise remains to be determined but appears to reside in the exercising muscle (38) and to be related to the temporal profile of changes in blood lactate (39, 55). Although few studies have examined the V˙O2 slow component during treadmill running, it appears that its magnitude is lower in running than in cycling (10, 31). However, in the previous studies that have assessed V˙O2 kinetics in running, the magnitude of the slow component has been determined rather simplistically by calculating the increase in V˙O2 between 3 and 6 min of exercise (28, 31) or between 3 min of exercise and the time at which exhaustion was reached (8, 10). It has been shown that the V˙O2 response to a square-wave heavy exercise challenge is better described by using three exponential terms, with the three terms describing the cardiodynamic phase (phase I), the fast component (phase II), and the V˙O2 slow component (phase III), respectively (7).

The V˙O2 slow component has been suggested to be an important determinant of exercise tolerance in both patient populations (54) and athletic groups (18). After a period of endurance training, the steady-state V˙O2 during moderate-intensity, constant-load cycle ergometry is unchanged (16, 21, 22), although the phase II...
ENDURANCE TRAINING AND $\dot{V}$O$_2$ KINETICS

Michael J. Mearns, Douglas J. Mather, Paul M. Joynt, and Graham P. Cleland

Keywords: Maximum oxygen uptake; Running speed conditions; Heavy-intensity exercise; Moderate-intensity exercise; Slow component oxygen uptake; Endurance training; Lactate accumulation.

Abstract: Endurance training increases the capacity of the cardiovascular system to transport oxygen to exercising muscles, allowing the body to achieve a higher VO$_2$ max during exercise. However, the effects of endurance training on the kinetics of VO$_2$ has not been fully understood. The purpose of this study was to investigate the effects of endurance training on the kinetics of VO$_2$ during running.

Methods: Twenty-three subjects (14 men; age 22 ± 3 yr, height 1.75 ± 0.06 m, body mass 70.3 ± 9.1 kg; means ± SD) volunteered to take part in this study. The subjects were young, healthy physical education students who were recreationally active and not specifically trained for endurance running. Subjects were fully familiar with the laboratory environment and were accustomed to treadmill running before the study commenced. The subjects gave written, informed consent after the experimental procedures and the associated risks and benefits of participation were explained. The procedures used in this study were approved by the Chelsea School Ethics Committee, University of Brighton. The subjects were all fully familiar with laboratory exercise testing procedures, having previously participated in other similar studies.

Subjects were instructed to arrive at the laboratory in a rested and fully hydrated state, at least 3 h postprandial, and to avoid strenuous exercise in the 48 h preceding a test session. For each subject, tests took place at the same time of day (±2 h) to minimize the effects of diurnal biological variation on the results.

Procedures. All exercise tests were performed on a motorized treadmill (Woodway, Cardiokinetics, Salford, UK), with the grade set at 1% (29). During the exercise tests, pulmonary gas exchange was determined breath by breath.

Subjects breathed through a low-resistance mouthpiece and turbine assembly. Gases were continuously drawn from the mouthpiece through a 2-m capillary line of small bore (0.5 mm) at a rate of 60 ml/min and were analyzed for $O_2$, $CO_2$, and $N_2$ concentrations by a quadrupole mass spectrometer (CaSE QP9000, Gillingham, Kent, UK), which was calibrated before each test by use of gases of known concentration. Expiratory volumes were determined by using a turbine volume transducer (Interface Associates). The volume and concentration signals were integrated by computer, after analog-to-digital conversion, with account taken of the gas transit delay through the capillary line. Respiratory gas exchange variables ($V_{O_2}$, carbon dioxide production, and minute ventilation ($Ve$)) were calculated and displayed for every breath. The VO$_2$ values were not treated with an alveolar correction algorithm and therefore represent values measured at the mouth. Heart rate was recorded telemetrically throughout the exercise tests (Polar Electro Oy, Kempele, Finland).

On the first visit to the laboratory, the subjects performed an incremental treadmill test to volitional exhaustion for the determination of LT and VO$_2$ max. The initial treadmill speed was between 6.0 and 7.0 km/h for the women and between 8.0 and 9.0 km/h for the men. The subjects completed 6–8 sub-maximal stages of 4-min duration, with running speed increased by 1.0 km/h between stages (30). At the end of each stage, the subjects grasped the handrails and moved their feet astride the treadmill belt. A fingertip capillary blood sample (−25 µl) was collected into a capillary tube for subsequent analysis of blood lactate concentration (lactate) using an automated lactate analyzer (YSI 2300, Yellow Springs, OH). The subjects recommenced running within 10–15 s. When heart rate exceeded 90% of the known or age-predicted maximum heart rate, the running speed was increased by 1.0 km/h per minute until the subject reached volitional exhaustion. Plots of blood lactate against running speed and VO$_2$ were provided to two independent reviewers, who determined the LT as the first sustained increase in blood lactate above baseline levels. The breath-by-breath gas exchange data collected during these tests were averaged over consecutive 30-s periods. The VO$_2$ max was defined as the average VO$_2$ attained in the last 30 s of the tests. Attainment of VO$_2$ max was confirmed by a high incidence of a plateau phenomenon in VO$_2$ (96%), respiratory exchange ratio values above 1.10 (78%), and heart rates within 5 beats/min of age-predicted maximum (92%). In all subjects, at least two of the three criteria were met. The running speed at VO$_2$ max was estimated by extrapolation of the sub-LT relationship between VO$_2$ and running speed. Individual regression equations were calculated using the VO$_2$-running speed relationship for all exercise stages below the LT. The VO$_2$ max was then entered into the equation given, providing an estimate of the running speed at VO$_2$ max ($v_{VO_2 max}$, where $v$ is velocity). The individual regression equations were then used to calculate the running speeds corresponding to 80% of the VO$_2$ at LT and 50% of the difference between the VO$_2$ at LT and VO$_2$ max (50% ∆).

Subsequently, subjects performed a series of square-wave transitions at the two exercise intensities on separate days. The subjects completed three transitions to the moderate-intensity running speed or two transitions to the heavy-intensity running speed. The days on which the moderate- and heavy-intensity exercise bouts were performed were presented to the subjects in random order. The exercise protocol started with 2 min of standing rest, with the subject’s feet astride the moving treadmill belt and hands holding the guard rails. Subjects commenced running by supporting their body mass with their hands on the guard rails until leg speed matched treadmill belt speed, after which they let go of the handrails and commenced running. This transition from rest to exercise took 3–5 s. The exercise continued for 6 min. At the end of the 6-min period, the subjects grasped the guard rails and moved their feet astride the treadmill belt. Fingertip capillary blood samples were taken immediately before and immediately after exercise. The difference between the end-exercise lactate and the resting lactate was expressed as a delta value (Δ[ lactate]). For the moderate-intensity running speed condition, the subjects completed three identical transitions on the same day, with at least 30 min of rest between the trials. For the heavy-intensity running speed condition, the subjects completed two identical transitions on the same day, with at least 60 min of rest between the trials. Before the second transition, a capillary blood sample was taken to ensure that lactate concentration had returned to resting levels. These procedures were replicated at the end of the training period. In addition, a randomly chosen subgroup of 10 subjects (5 men) also performed transitions to the recalculated 50% ∆ running speeds derived from the post-training incremental test.
Training. After completion of the initial testing battery, the subjects began a 6-wk program of endurance training. Table 1 describes the training undertaken and shows the increases in training duration and frequency over the 6-wk period. For the continuous sessions, the LT was used to regulate the training intensity because this should provide a high-quality aerobic training stimulus without the accumulation of lactate that might compromise training duration. It has been shown that this type of training significantly im-

\[
V_{O2}(t) = V_{O2}(b) + A_0 \cdot (1 - e^{-rt}) + A_1 \cdot (1 - e^{-rt - TD_1}) + A_2 \cdot (1 - e^{-rt - TD_2})
\]

proves the LT (33). Although the average intensity of the continuous and interval training sessions was similar, the interval efforts were designed to be appreciably above the LT to invoke lactate accumulation. In a previous study, this training program significantly increased the running speed at LT, the running speed at the maximal lactate steady state, and the VO2 max in 16 subjects of similar initial fitness status to the subjects of the present study (11).

To quantify the training undertaken, all subjects were issued telemetric heart rate monitors and instructed to collect and download the heart rate data for each training session completed. For the continuous training sessions, subjects exercised at the heart rate measured at the LT (±5 beats/min) in the pretraining incremental test. The interval training sessions involved a 5-min warm-up jog, then 10 efforts of 2-min duration (at a heart rate of ~10 beats/min above the heart rate at LT) separated by a 2-min jog recovery (at a heart rate of ~10 beats/min below the heart rate at LT), and finally a 5-min jog. Mean running speeds across the group were 10.4 ± 1.9 km/h (72.6 ± 6.0% VO2 max or ~67% V-VO2 max) for the continuous session and 11.9 ± 2.2 km/h (76.9 ± 4.3% VO2 max or ~77% V-VO2 max) for the interval session. Heart rate data from individual training sessions were checked on a weekly basis to ensure that subjects exercised at the prescribed heart rates. All subjects completed training diaries listing all physical activity performed over the 6-wk study period so that training compliance could be ascertained. In addition, subjects recorded their diet before the pretraining laboratory visits and replicated this diet for their return visits to the laboratory at the end of the training period.

Data analysis. For each exercise transition, the breath-by-breath data were interpolated to give second-by-second values and were time aligned to the start of exercise. The transitions for each intensity were then averaged to enhance the underlying response characteristics.

Table 1. Progression of training duration and frequency through 6 wk of training

<table>
<thead>
<tr>
<th>Week</th>
<th>No. of sessions</th>
<th>Duration</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>20 min</td>
<td>Continuous</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>30 min</td>
<td>Interval</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>23 min</td>
<td>Continuous</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>30 min</td>
<td>Interval</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>26 min</td>
<td>Continuous</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>30 min</td>
<td>Interval</td>
</tr>
<tr>
<td>4, 5, and 6</td>
<td>3</td>
<td>30 min</td>
<td>Continuous</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>30 min</td>
<td>Interval</td>
</tr>
</tbody>
</table>

Nonlinear regression techniques were used to fit the time course of the VO2 response after the onset of exercise with an exponential function. An iterative process was used to minimize the sum of squared errors. The empirical model consisted of two (moderate exercise) or three (heavy exercise) exponential terms, each representing one phase of the response (see Ref. 6). The first exponential term started with the onset of exercise (time = 0), whereas the other terms began after independent time delays

\[
A_0' = A_0 \cdot (1 - e^{-TD_1})
\]

The VO2 at the end of phase 1 (A0) and the amplitude of phase 2 (A1) were summed to calculate the amplitude of phase 2 (A1). The amplitude of the slow component was determined as the increase in VO2 from TD2 to the end of exercise (defined as A2), rather than from the asymptotic value (A0), which lies beyond physiological limits (6). The slow component was also described by using the difference in VO2 between 3 and 6 min of exercise (using the average VO2 values between 2.75 and 3.00 and between 5.75 and 6.00 min). The gain of the phase II exponential response (A1/running speed expressed relatively to body mass) for the two exercise intensities was also calculated.

Statistical analysis. Paired t-tests were used to determine the significance of any differences in the measured variables before vs. after training. Statistical significance was set at the 5% level. A repeated-measures ANOVA (Wilks lambda) was used to identify differences in the subgroup of subjects. Pearson product-moment correlation coefficients were used to examine the significance of relationships between the slow component and changes in blood lactate and V̇e. The results are presented as means ± SE.

RESULTS

Table 2 shows the effect of training on the physiological variables that were measured during the incremental treadmill test. There were significant increases in VO2 max (t22 = -4.22, P <0.001), the VO2 at the LT (t22 = -3.78, P <0.001), and a significant reduction in maximal heart rate (t22 = 3.36, P = 0.03).

For moderate exercise, which caused no increase in blood lactate above baseline, the kinetics of the VO2 response were fit with two exponential terms. The VO2 kinetics for moderate exercise, including the amplitudes, time constants, and time delays, were unchanged with training (Table 3). For heavy exercise, which caused a significant increase in blood lactate above baseline, the kinetics of the VO2 response were fit
with three exponential terms. Endurance training caused a significant reduction in the blood lactate accumulation ($t_{22} = 3.11, P = 0.005$) but did not affect the time delays or the time constants of the exponential model or the amplitude of phase II (Table 3). It was of interest that the time constant for phase II was unchanged with training ($t_{22} = 0.49, P = 0.63$). However, it should be noted that our subjects were relatively fit ($V\dot{O}_2_{\text{max}}$ of 40.2 ± 1.2 ml·kg$^{-1}$·min$^{-1}$), $t_1$ for heavy exercise was reduced from 31.5 ± 1.0 to 19.5 ± 1.5 s by the training period ($t_5 = 2.92, P = 0.033$).

The amplitude of the $V\dot{O}_2$ slow component was significantly reduced with training both in absolute terms (Fig. 1, $t_{22} = 3.53, P = 0.002$) and when expressed as a proportion of the total $V\dot{O}_2$ response to the exercise (Table 3, $t_{22} = 3.57, P = 0.002$). All subjects demonstrated an attenuated slow component with training, although the magnitude of the reduction varied between individuals (range 8–308 ml·min$^{-1}$). This reduction in the slow component resulted in a significantly reduced end-exercise $V\dot{O}_2$ ($t_{22} = 4.90, P = 0.004$). Neither the increase in $V\dot{O}_2_{\text{max}}$ nor the increase in LT was correlated with the decrease in the amplitude of $V\dot{O}_2$ slow component ($r = 0.03$ and $r = 0.04$, respectively).

There was no significant improvement in running economy with training in the subjects. The average steady-state $V\dot{O}_2$ at 80% LT (calculated from the three transitions of 6-min duration that our subjects performed at this exercise intensity) was not significantly different before and after training. Furthermore, there was no consistent or significant reduction in $V\dot{O}_2$ during the submaximal stages of the incremental test.

In the 10 subjects who performed a bout of heavy exercise at 50%Δ recalculated after training, despite increases in the running speed utilized and the amplitude of phase II ($t_9 = -2.7, P = 0.02$), the slow component amplitude was similar compared with the pretraining 50%Δ condition (Table 4, $t_9 = 1.37, P = 0.20$). Data from a typical subject can be seen in Fig. 2.

Before training, there was a strong correlation between the $V\dot{O}_2$ slow component and the increase in blood lactate above baseline ($r = 0.69; P < 0.001$). However, after training, the strength of this association diminished ($r = 0.45; P = 0.03$). The relationship between the reduction in blood lactate accumulation and the reduction in the slow component with training was not significant ($r = 0.39; P = 0.65$). Similarly, there was a strong relationship between the $V\dot{O}_2$ slow component and the increase in $V\dot{E}$ over the same time frame before training ($r = 0.70; P < 0.01$), which diminished after training ($r = 0.20; P = 0.86$).
was a significant relationship between the reduction in
\( V\dot{E} \) and the reduction in the slow component with training \((r = 0.46; P = 0.03)\).

**DISCUSSION**

The principal finding of this study was that a 6-wk period of endurance training caused an attenuation of the slow component in running of \(-35\%\), i.e., from 321 to 217 ml/min, on average. This is of interest in that our subjects were young, healthy subjects who were actively engaged in sports and were of a relatively high fitness at entry into the study. These results suggest that the \( V\dot{O}_2 \) slow component can be reduced by a short period of endurance training despite relatively small changes in traditional measures of aerobic fitness such as \( V\dot{O}_2 \) max and LT.

The endurance training program that our subjects undertook was successful in causing a significant improvement in the \( V\dot{O}_2 \) at LT \((-4\%)\) and \( V\dot{O}_2 \) max \((-3\%)\), although these improvements were less than those reported in other training studies (16, 23, 53). Our subjects recorded their training in diaries over the course of the study and also used heart rate monitors to guide their training. From the heart rate records, subjects adhered to their prescribed training intensities, and, from diary records, the training compliance of the subjects was \(87\\%\pm1.7\%\). The mean pretraining \( V\dot{O}_2 \) max of \(55\ ml\cdot kg^{-1} \cdot min^{-1}\) highlights the fact that our subjects were already of good aerobic fitness on recruitment to the study. The rather small increases in \( V\dot{O}_2 \) max should therefore not be considered surprising.

In our study, there were no significant relationships between \( t_1 \) and \( V\dot{O}_2 \) max for moderate or heavy exercise either before or after training. Our results differ from those of Powers et al. (41), who reported that, in subjects of similar training status to subjects of the present study, \( V\dot{O}_2 \) kinetics were faster in trained subjects with the higher \( V\dot{O}_2 \) max values. Our results also contrast with the study of Chilibeck et al. (14), which showed significantly faster \( V\dot{O}_2 \) kinetics in subjects

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Pretraining</th>
<th>Posttraining</th>
<th>Posttraining “New”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Running speed, km/h</td>
<td>12.7 ± 0.9</td>
<td>12.7 ± 0.9</td>
<td>13.6 ± 0.9</td>
</tr>
<tr>
<td>( A_0 ), ml/min</td>
<td>1,112 ± 145</td>
<td>1,110 ± 102</td>
<td>1,090 ± 94.8</td>
</tr>
<tr>
<td>( t_0 ), s</td>
<td>4.2 ± 1.2</td>
<td>4.8 ± 0.7</td>
<td>3.4 ± 1.1</td>
</tr>
<tr>
<td>( TD_1 ), s</td>
<td>17.7 ± 1.3</td>
<td>18.5 ± 0.6</td>
<td>16.7 ± 0.9</td>
</tr>
<tr>
<td>( A_1 ), ml/min</td>
<td>2,684.7 ± 218</td>
<td>2,663.9 ± 208</td>
<td>2,825.7 ± 223*</td>
</tr>
<tr>
<td>( t_1 ), s</td>
<td>17.5 ± 1.2</td>
<td>18.4 ± 1.3</td>
<td>18.5 ± 1.3</td>
</tr>
<tr>
<td>Gain, ml·kg^{-1}·km^{-1}</td>
<td>172.9 ± 5.3</td>
<td>172.9 ± 4.2</td>
<td>170.5 ± 4.9</td>
</tr>
<tr>
<td>MRT, s</td>
<td>57.6 ± 2.6</td>
<td>49.7 ± 2.3*</td>
<td>53.4 ± 1.2*</td>
</tr>
<tr>
<td>( TD_2 ), s</td>
<td>111.4 ± 9.2</td>
<td>115.3 ± 8.2</td>
<td>117.1 ± 5.9</td>
</tr>
<tr>
<td>( A_2 ), ml/min</td>
<td>314.2 ± 45.1</td>
<td>213.2 ± 30.1*</td>
<td>249.4 ± 34.5</td>
</tr>
<tr>
<td>Relative ( A_2 ), %</td>
<td>10.3 ± 1.2</td>
<td>7.2 ± 0.9*</td>
<td>7.9 ± 0.7</td>
</tr>
<tr>
<td>( t_2 ), s</td>
<td>245.6 ± 22.9</td>
<td>269.5 ± 19.6</td>
<td>286.7 ± 46.3</td>
</tr>
<tr>
<td>EE ( V\dot{O}_2 ), ml/min</td>
<td>2,998.9 ± 243</td>
<td>2,877.1 ± 228</td>
<td>3,288.1 ± 235*</td>
</tr>
<tr>
<td>( \Delta V\dot{E} ), l/min</td>
<td>20.3 ± 2.3</td>
<td>10.3 ± 2.3*</td>
<td>13.4 ± 2.2</td>
</tr>
<tr>
<td>EE HR, beats/min</td>
<td>176 ± 3</td>
<td>172 ± 3*</td>
<td>178 ± 3</td>
</tr>
<tr>
<td>( \Delta [lactate] ), mM</td>
<td>3.5 ± 0.4</td>
<td>3.3 ± 0.3</td>
<td>4.3 ± 0.4</td>
</tr>
</tbody>
</table>

Values are means ± SE. Posttraining “new” refers to the data from the recalculated 50% \( \Delta \) trial. *Significantly different from pretraining value, \( P < 0.05 \) (exact \( P \) values given in text).
with higher $V_{O2\ max}$ values in 16 young subjects. However, their subjects were of generally lower aerobic fitness and showed greater heterogeneity in $V_{O2\ max}$ ($25-59 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$) than our subjects.

The training program had no effect on the kinetics of the $V_{O2}$ response to moderate exercise or on phase II during heavy exercise. These results are in contrast to other studies that have shown a speeding of $V_{O2}$ kinetics with training for exercise intensities up to $\sim 70\% V_{O2\ max}$ (21, 22, 58). The relatively high aerobic fitness of our subjects at the start of the training study may provide an explanation for this. Indeed, in the six subjects with the lowest initial $V_{O2\ max}$ values ($\sim 40 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$), we found that $\tau_1$ was significantly decreased (i.e., the adjustment of $V_{O2}$ was speeded) by training for heavy exercise (by 12 s) but not for moderate exercise. The faster kinetics of phase II in our low-fit subjects may be related to improved oxygen delivery to muscle or to increases in muscle mitochondrial density with training, which would improve the sensitivity of respiratory control (20).

Another explanation for the apparent discrepancy between the present study and previous literature is that earlier studies (21, 22, 41) did not attempt to partition out any effect of the possible development of the $V_{O2}$ slow component on the total $V_{O2}$ response but simply calculated the half-time of the response to the steady state. It is not clear in these studies whether the subjects were exercising above or below their LT. When the mean response time is considered in the present study, it can be seen that, whereas the overall $V_{O2}$ kinetic response for moderate exercise was unchanged at $\sim 22$ s, the mean response time was significantly decreased for heavy exercise (from $\sim 58$ to $47$ s; $t_{22} = 4.2, P < 0.001$; see Table 3). However, the latter results from the reduction of the slow component and not from any speeding of phase II.

Our results that the time constant of phase II does not differ significantly above and below the LT (Table 3) supports the findings of some (5, 7, 12), but not all (34), previous studies using cycle exercise. To consider whether the lack of difference in $\tau_1$ between moderate and heavy exercise might be a consequence of the fitness of the subjects, we looked at the unfit subgroup. Interestingly, this subgroup had a considerably slower $\tau_1$ in heavy exercise ($\sim 31$ s) than in moderate exercise ($\sim 17$ s) pretraining. The period of endurance training speeded the phase II response in heavy exercise ($\sim 20$ s) but not in moderate exercise ($\sim 13$ s), bringing $\tau_1$ near to the values of the other 17 subjects and to the whole-group mean ($\sim 19$ s). This would suggest that a period of endurance training speeds suprathreshold kinetics in less fit individuals, causing $\tau_1$ to reduce toward subthreshold values. Despite the training improvement, the heavy exercise $\tau_1$ was still slower than in moderate exercise in this group. This tends to support the work of Paterson and Whipp (34), who suggest slower kinetics during suprathreshold work. However, further specific studies of treadmill running are clearly required before firm conclusions can be drawn.

The amplitude of phase II was linearly related to exercise intensity because the gain ($A_1$) was similar before and after training ($t_{22} = 0.44, P = 0.20$). This is in accordance with previous work (7, 12, 34) and confirms that the slow component is a phenomenon of delayed onset that causes $V_{O2}$ to rise above (rather than toward) the predicted steady-state value.

Despite the relatively small increases in LT and $V_{O2\ max}$ caused by the training program, there was a substantial and significant reduction in the slow component for the same running speed posttraining. This
was true even when the six less fit subjects were removed from the analysis and when men and women were analyzed separately. The reduction of the \( \text{VO}_2 \) slow component has significant implications for exercise tolerance in athletic, sedentary, and patient populations. For the competitive athlete, the ability to run at a faster running speed for a given metabolic stress (i.e., same \( \text{VO}_2 \) slow component) may result in performance enhancement. This is exemplified by the data from the subgroup within the present study (Table 4). In addition to a reduced slow component at the same absolute exercise intensity, these subjects were able to run at a faster speed while eliciting a slow component of similar magnitude (\( \sim 250–300 \text{ ml/min} \)) to that of pretraining heavy exercise. For patients with cardiac and/or pulmonary disorders, even very low exercise intensities, such as slow walking, represent a severe metabolic stress (50). Endurance training will increase the range of intensities over which the \( \text{VO}_2 \) slow component would not be expected to develop. This would improve the functional ability of these individuals irrespective of any change in LT or \( \text{VO}_{2 \text{max}} \) (36).

This study is the first to investigate the effect of training on \( \text{VO}_2 \) kinetics by using mathematical modeling. Previous studies (13, 57) have defined the slow component as the increase in \( \text{VO}_2 \) between 3 min and the end of exercise (\( \Delta \text{VO}_2 \)). The slow component first becomes evident at about 2 min into exercise (\( \sim 114 \pm 6.0 \text{ s} \); see Table 3 and Ref. 6). Therefore, defining the slow component as an increase in \( \text{VO}_2 \) above the value at 3 min of exercise will significantly underestimate the magnitude of the slow component. Indeed, calculating the \( \Delta \text{VO}_2 \) in the present study showed a reduction in the slow component of \( \sim 60 \text{ ml/min with training} \) (193 ± 22 vs. 130 ± 15 ml/min, \( t_{22} = 3.18, P = 0.004 \)). This more simplistic characterization of the slow component might also explain why some studies have reported that the slow component is trivially small during treadmill running (8, 10).

Our results are similar to those of Casaburi et al. (13) and Womack et al. (57), who showed that the \( \text{VO}_2 \) slow component could be significantly reduced after 8 wk and 6 wk, respectively, of cycle ergometer training. In agreement with Casaburi et al. (13), we found that the reduction in the slow component was related to the reduction in the \( \Delta \text{VE} \) and the \( \Delta [\text{lactate}] \), although the latter relationship did not attain significance in our study. We did not assess the relationship between the reduction in the \( \text{VO}_2 \) slow component and changes in other putative mediators of the slow component such as body temperature and catecholamine concentrations. However, previous studies have shown that infusion of epinephrine during exercise has no effect on the exercise \( \text{VO}_2 \) despite causing significant increases in plasma epinephrine and lactate (19, 37). Furthermore, Casaburi et al. found no significant relationship between the changes in catecholamines and the changes in the slow component that occurred with endurance training. In the same study, there was no significant relationship between changes in rectal temperature and changes in the slow component with training (13).

It was of interest that the strong relationship between the \( \Delta [\text{lactate}] \) and the slow component found before training (\( r = 0.69 \)) was reduced considerably after training (\( r = 0.45 \)). Furthermore, the changes in lactate and the slow component with training were not significantly related. Several previous cross-sectional studies have shown a close relationship between the magnitude of the blood lactate increase and the slow component for cycle exercise (39, 42, 55). It has been suggested that lactic acidosis is important in the maintenance of muscle \( \text{PO}_2 \) during heavy exercise (48), and that the metabolic cost of glycogenesis from lactate during exercise above the LT may contribute to the development of the slow component (13). The proportion of the lactate produced during exercise the fate of which is gluconeogenesis as opposed to oxidation is not certain, but it can be calculated that the additional oxygen cost of lactate catabolism is not sufficient to make a significant contribution to the slow component (54). In two recent studies, a weaker relationship between lactate and the slow component was reported in runners (\( r = 0.36 \); Ref. 31) and triathletes (\( r = 0.12 \); Ref. 9) during treadmill exercise. In these studies, the slow component was significantly greater for cycling than for running for the same elevated blood lactate concentrations (10, 31). These results support the suggestion that the relationship between lactate increase and the slow component is coincidental rather than causal. This interpretation is supported by studies that show an unchanged \( \text{VO}_2 \) when 1) blood lactate is increased through infusion of epinephrine during exercise (19, 37), 2) exercise blood lactate is lowered by the inhibition of carbonic anhydrase with acetazolamide (45), and 3) \( l-(+) \)-lactate is infused into the arterial blood supply of dogs who were exercised using electrical stimulation (37). In addition, the time at which the \( \text{VO}_2 \) slow component emerges (\( \sim 80–140 \text{ s} \)) is much later than the time at which lactate appears in the femoral vein (42).

The \( \text{VO}_2 \) slow component was significantly related to the change in \( \text{VE} \) over the same period of time before (\( r = 0.70 \)) but not after (\( r = 0.20 \)) training. The reduction in \( \text{VE} \) for the same running speed after training was also significantly related to the reduction in the slow component at that running speed. This, of course, does not necessarily indicate that the increase in \( \text{VE} \) over time during heavy exercise is an important mediator of the slow component, because a reduced \( \text{VO}_2 \) with training is likely to require a reduced \( \text{VE} \). The lowering of blood lactate concentrations caused by training would reduce the ventilatory load consequent to a reduced bicarbonate buffering of the lactic acidosis (13). Using the estimates of Aaron et al. (1) that the oxygen cost of \( \text{VE} \) ranges from 1.79 ml O\(_2\) per liter for ventilatory rates of 63–79 l/min to 2.85 ml O\(_2\) per liter for ventilatory rates of 117–147 l/min, the reduction in the \( \text{VE} \) we observed with training (Table 3) could account for only 9–14% of the reduction in the slow component. These results are consistent both with pre-
vious studies showing that $V\dot{E}$ contributes minimally ($\leq 20\%$) to the slow component (28, 57) and with the study of Poole et al. (38), which demonstrated that $\sim 86\%$ of the $V\dot{O}_2$ slow component could be accounted for by processes inherent to the exercising limbs.

One possibility for the significant reduction in the slow component posttraining is an alteration in the motor unit recruitment pattern. Both electromyographic (46) and glycogen depletion studies (49) indicate that type II muscle fibers are recruited at exercise intensities associated with the slow component. It is known that the type II muscle fiber is less efficient than the type I muscle fiber and that the ratio of phosphate produced to oxygen molecule consumed (P-O) is $\sim 18\%$ lower in the isolated type II fiber due, in part, to a greater reliance on the $\alpha$-glycerophosphate shuttle over the malate-aspartate shuttle (15, 44, 52, 56). This would predict a greater $V\dot{O}_2$ for any given rate of ATP resynthesis. Barstow et al. (6) showed that the contribution of the slow component to the total $V\dot{O}_2$ response to 8 min of heavy exercise was significantly positively related to the proportion of type II fibers in the vastus lateralis. Endurance training is known to result in a significant enhancement in the mitochondrial density and the capillarity of type I and type II muscle fibers (2, 24). Interconversion of fiber types may also be possible (type IIb $\rightarrow$ IIa $\rightarrow$ I) (2, 26), although this has not been demonstrated in short-term human training studies. Although we cannot be certain of the extent to which our training program required the recruitment of type II muscle fibers, changes such as an increased muscle mitochondrial content and improved perfusion in type I muscle fibers might result in the recruitment of fewer type II motor units for the same exercise intensity after training.

In conclusion, we have shown that an endurance training program that produced small but significant increases in $V\dot{O}_2_{\text{max}}$ and LT did not affect the $V\dot{O}_2$ response to moderate exercise or the phase II response during heavy exercise. However, the training led to a significant reduction in the $V\dot{O}_2$ slow component at the same absolute running speed. Although we did not measure performance directly, our results demonstrating a slow component of similar magnitude when individuals exercised at higher running speeds after training suggests improved exercise tolerance. We speculate that the reduced slow component may be linked to the recruitment of fewer low-efficiency type II muscle fibers for the same exercise intensity after training.

REFERENCES

8. Billat V, Binse V, Petit B, and Koralsztein JP. High level runners are able to maintain a $V\dot{O}_2_{\text{steady-state}}$ below $V\dot{O}_2_{\text{max}}$ in an all-out run over their critical velocity. Arch Physiol Biochem 107: 1–8, 1998.