Effect of endurance training on muscle TCA cycle metabolism during exercise in humans

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Howarth, Krista R., Paul J. LeBlanc, George J. F. Heigenhauser, and Martin J. Gibala. Effect of endurance training on muscle TCA cycle metabolism during exercise in humans. J Appl Physiol 97: 579–584, 2004.—We tested the theory that links the capacity to perform prolonged exercise with the size of the muscle tricarboxylic acid (TCA) cycle intermediate (TCAI) pool. We hypothesized that endurance training would attenuate the exercise-induced increase in TCAI concentration ([TCAI]); however, the lower [TCAI] would not compromise cycle endurance capacity. Eight men (22 ± 1 yr) cycled at ~80% of initial peak oxygen uptake before and after 7 wk of training (1 h/day, 5 days/wk). Biopsies (vastus lateralis) were obtained during both trials at rest, after 5 min, and at the point of exhaustion during the pretraining trial (42 ± 6 min). A biopsy was also obtained at the end of exercise during the posttraining trial (91 ± 6 min). In addition to improved performance, training increased ([P < 0.05]) peak oxygen uptake and citrate synthase maximal activity. The sum of four measured TCAI was similar between trials at rest but lower after 5 min of exercise posttraining [2.7 ± 0.2 vs. 4.3 ± 0.2 mmol/kg dry wt (P < 0.05)]. There was a clear dissociation between [TCAI] and endurance capacity because the [TCAI] at the point of exhaustion during the pretraining trial was not different between trials (posttraining: 2.9 ± 0.2 vs. pretraining: 3.5 ± 0.2 mmol/kg dry wt), and yet cycle endurance time more than doubled in the posttraining trial. Training also attenuated the exercise-induced decrease in glutamate concentration (posttraining: 4.5 ± 0.7 vs. pretraining: 7.7 ± 0.6 mmol/kg dry wt) and increase in alanine concentration (posttraining: 3.3 ± 0.2 vs. pretraining: 5.6 ± 0.3 mmol/kg dry wt; P < 0.05), which is consistent with reduced carbon flow through alanine aminotransferase. We conclude that, after aerobic training, cycle endurance capacity is consistent with reduced carbon flux through alanine aminotransferase (AAT; glutamate + pyruvate ↔ alanine + 2-oxoglutarate) owing to an increase in pyruvate availability when its rate of production from glycolysis transiently exceeds its rate of oxidation in the pyruvate dehydrogenase reaction (11, 21). A prominent theory in the literature is that the observed increase in muscle [TCAI] (brackets denote concentration) is necessary to attain rates of aerobic energy provision during strenuous exercise (21, 25–27). Indirect evidence commonly cited to support this hypothesis includes the following:

1) the concentration of muscle TCAI declines during prolonged exercise to fatigue (11, 21); 2) carbohydrate (CHO) supplementation before (23) or during prolonged exercise (22) increases the muscle concentration of TCAI during the latter stages of prolonged exercise and is associated with increased endurance capacity; and 3) patients with McArdle’s disease show little increase in muscle TCAI during exercise and have poor endurance capacity (20).

In contrast to the theory described above, several recent studies that manipulated the concentrations of muscle TCAI during exercise concluded that the contraction-induced expansion of the TCA cycle pool was unrelated to the capacity for oxidative energy delivery (4, 8, 10). However, two of these studies employed interventions that augmented the rate of TCAI expansion (4, 10), and it can be argued that a more appropriate strategy to examine this issue would be to attenuate the magnitude of TCAI expansion during exercise. Recently, our group employed a “short-term” exercise training model and, for the first time in humans, showed that the acute expansion of the muscle TCAI pool could be attenuated during exercise (8). The reduction in [TCAI] did not appear to compromise aerobic energy delivery, as judged by changes in phosphocreatine degradation and lactate accumulation after 5 min. However, the design of that study (8) incorporated a fixed-duration exercise model rather than a volitional fatigue protocol. Hence, we were unable to discern whether endurance capacity was in fact altered by a reduction in [TCAI] during exercise or whether the point of volitional fatigue during a prolonged exercise bout coincided with a specific “level” of TCAI, as implied by several authors (21, 25–27).

The primary purpose of the present investigation was to examine the effect of endurance training on the intermediary metabolism of muscle TCAI at rest and during an acute bout of prolonged exercise in humans. An important novel aspect of the study was that subjects were instructed to exercise to exhaustion before and after training, and muscle was sampled during and at the end of exercise. By incorporating this design, we sought to directly test the theory that links the size of the TCAI pool with the capacity to perform prolonged exercise. We hypothesized that aerobic training would attenuate the exercise-induced expansion of the TCA cycle pool; however, the lower [TCAI] would not compromise cycle endurance capacity. A secondary purpose of the study was to examine potential changes in the metabolism of glutamate and alanine (i.e., the key amino acids involved in the AAT reaction) because the effect of endurance training on muscle amino acids

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has not been previously reported in humans. We hypothesized that the resting concentrations of glutamate and alanine would be higher in trained muscle, on the basis of the results of a cross-sectional study published by Graham et al. (12); however, the exercise-induced changes in these two amino acids would be attenuated after training.

METHODS

Subjects

Eight healthy men with mean age, height, and body mass of 21.6 ± 1.0 yr, 178.9 ± 2.0 cm, and 91.6 ± 4.3 kg, respectively, volunteered for the study. None of the subjects was specifically trained in cycling exercise. The experimental procedures and potential risks were fully explained to the subjects before the study, and all subjects provided written, informed consent. The experimental protocol was approved by the McMaster University and Hamilton Health Sciences Research Ethics Board.

Preexperimental Procedures

Subjects initially performed a progressive exercise test on an electrically braked cycle ergometer (Lode BV, Excalibur Sport V2.0) to determine their $\dot{V}O_2$ peak by use of an online gas-collection system (Moxus modular $\dot{V}O_2$ system, AEI Technologies, Pittsburgh, PA). The value used for $\dot{V}O_2$ peak corresponded to the highest value achieved over a 30-s collection period. Subjects subsequently performed a familiarization ride to determine the workload that elicited ~80% of their $\dot{V}O_2$ peak. Subjects were instructed to refrain from exercise or alcohol consumption for 48 h before each experimental trial. They were also advised to consume the same types and quantities of food during the 24 h before each experimental trial, and all subjects maintained pretrial food diaries. The diaries were subsequently analyzed for nutritional content (Nutritionist 5, version 1.7, First DataBank, San Bruno, CA) to confirm that total energy intake and proportion of energy from CHO, fat, and protein were similar before each experimental trial. Subsequent dietary analyses revealed that subjects were extremely compliant: during the 24 h before each experimental trial, and all subjects were also advised to consume the same types and quantities of food during the 24 h before each experimental trial, and all subjects maintained pretrial food diaries. The diaries were subsequently analyzed for nutritional content (Nutritionist 5, version 1.7, First DataBank, San Bruno, CA) to confirm that total energy intake and proportion of energy from CHO, fat, and protein were similar before each experimental trial. Subsequent dietary analyses revealed that subjects were extremely compliant: during the 24 h before each trial, subjects consumed 2,733 ± 196 kcal, 52% ± 3 CHO, 30% ± 3 fat, and 17% ± 2 protein before trial 1, and 2,768 ± 301 kcal, 53% ± 3 CHO, 29% ± 3 fat, and 18% ± 2 protein before trial 2. Three hours before each trial, all subjects consumed a standardized meal that contained 711 kcal and was derived from 87% CHO, 3% fat, and 10% protein. For a given subject, the two experimental trials were performed at the same time of day.

Experimental Exercise Trial

On arrival at the laboratory, a catheter was inserted into an antecubital vein, and the lateral portion of one thigh was prepared for the study. None of the subjects was specifically trained in cycling exercise. The experimental procedures and potential risks were fully explained to the subjects before the study, and all subjects provided written, informed consent. The experimental protocol was approved by the McMaster University and Hamilton Health Sciences Research Ethics Board.

Preexperimental Procedures

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Experimental Exercise Trial

On arrival at the laboratory, a catheter was inserted into an antecubital vein, and the lateral portion of one thigh was prepared for extraction of needle biopsy samples from the vastus lateralis muscle (3). Three or four small incisions were made into the skin and overlying fascia after injection of a local anesthetic (2% lidocaine). A biopsy and blood sample were obtained at rest, and then subjects commenced cycling to exhaustion on an electrically braked cycle ergometer (Lode BV) at a workload designed to elicit ~80% $\dot{V}O_2$ peak.Expired gases were collected during the 25- to 30-min period of exercise for determination of oxygen uptake, carbon dioxide production, and respiratory exchange rate using a Quinton metabolic cart (Quinton, Q-plex 1: Quinton Instrument). Heart rate was determined via a telemetry monitor (Polar Electro, Woodbury, NY). Blood samples were obtained after 10 and 30 min of exercise. Muscle biopsies were obtained after 5 min of exercise and at exhaustion (EndEx1). At 2 to 6 days after the experimental exercise trial, subjects initiated a 7-wk aerobic exercise training protocol as described below.
measurements were corrected to the peak total creatine concentration for a given subject.

**Blood Analyses**

Blood samples were collected into heparinized tubes. Two hundred microliters of whole blood were combined with 1,000 μl of 0.6 N PCA, vortexed, and centrifuged, and the supernatant was collected and stored at −86°C. The PCA extract was subsequently analyzed for glucose and lactate, by using enzymatic assays adapted for fluorometry (19).

**Statistics**

All variables that consisted of single pre- and postmeasurements, including exercise performance data and muscle enzyme activities, were analyzed with paired t-tests. All muscle metabolites were analyzed by a one-way ANOVA owing to the uneven number of pre- and posttraining time points. Blood metabolites were analyzed by a two-way ANOVA (pre/post training × time). When a significant main effect or interaction was identified, data were subsequently analyzed by use of a Tukey’s honestly significant difference post hoc test. Significance for all analysis was set at \( P \leq 0.05 \). All values are presented as means ± SE.

**RESULTS**

**Cardiorespiratory and Performance Data**

\( \dot{V}_\text{O}_2 \) peak increased by 6% after training (posttraining: 4.13 ± 0.13 vs. pretraining: 3.90 ± 0.15 l/min, \( P < 0.05 \)), and the power output required to elicit a training intensity equivalent to 80% \( \dot{V}_\text{O}_2 \) peak increased from 206 ± 5 to 217 ± 4 W (\( P < 0.05 \)). The absolute workload (206 ± 5 W) employed during the experimental exercise trial elicited 80 ± 3% of pretraining \( \dot{V}_\text{O}_2 \) peak during the first experimental exercise trial and 69 ± 2% of \( \dot{V}_\text{O}_2 \) peak after training. Exercise oxygen uptake during the experimental exercise trial was not different after training (pretraining: 3.03 ± 0.08 vs. posttraining: 2.88 ± 0.07 l/min, \( P > 0.05 \)). Mean cycling time during the posttraining trial was 116% longer (\( P < 0.05 \)) compared with pretraining (91 ± 6 vs. 42 ± 6 min), and this was accompanied by decreases (\( P < 0.05 \)) in heart rate, expired ventilation, and respiratory exchange rate during exercise (data not shown). Body mass was not different after training.

**Muscle TCAI**

There was no difference in the total concentration of the four measured TCAI (ΣTCAI) at rest; however, the acute exercise-induced expansion of the ΣTCAI was markedly reduced after training (Fig. 1). The ΣTCAI after 5 min of exercise was 45% lower (\( P < 0.05 \)) posttraining compared with pretraining. Moreover, the ΣTCAI at EndEx1 and EndEx2 during the posttraining trial (2.9 ± 0.2 and 3.1 ± 0.2 mmol/kg dry wt, respectively) were not different compared with 5 min of exercise. This contrasted from the pretraining trial, in which the ΣTCAI declined during exercise such that the value at EndEx1 (3.5 ± 0.2 mmol/kg dry wt) was lower (\( P < 0.05 \)) compared with 5 min of exercise. Values for the four individual TCAI are summarized in Table 1.

**Muscle Amino Acids**

There was no effect of training on the resting intramuscular concentrations of glutamate or alanine (Table 1). However, the net change in both amino acids from rest to 5 min of exercise was attenuated after training, such that the decrease in glutamate and increase in alanine were both reduced by ~40% (Fig. 2). Glutamate was lower during exercise compared with rest, and alanine was higher, in both experimental trials (\( P < 0.05 \)).

**Other Muscle Metabolites**

Resting [glycogen] was 58% higher (\( P < 0.05 \)) posttraining compared with pretraining and remained higher throughout exercise (Table 1). Net muscle glycogenolysis from rest to 5 min of exercise was lower (\( P < 0.05 \)) posttraining (pretraining: 60.3 ± 10.1 vs. posttraining: 29.3 ± 9.1 mmol/kg dry wt). Muscle lactate accumulation after 5 min of exercise was attenuated by 70% posttraining and remained 58% lower at EndEx1 compared with the same time point pretraining (Table 1). Muscle [pyruvate] increased (\( P < 0.05 \)) from rest during exercise, but there was no difference between trials with the exception of the EndEx1 time point (Table 1). Muscle [phosphocreatine] was 55% higher after 5 min of exercise posttraining and remained higher at EndEx1 compared with pretraining (\( P < 0.05 \)) (Table 1). There were no differences in muscle [ATP] or [free CoA] within or between trials at any time point (Table 1). Muscle [acetyl CoA] was higher (\( P < 0.05 \)) after 5 min of exercise compared with rest during the pretraining trial but declined thereafter and was not different from rest at EndEx1 (Fig. 3). During the posttraining trial, muscle [acetyl CoA] was higher (\( P < 0.05 \)) at all times during exercise compared with rest but not different compared with the value associated with fatigue (EndEx1) during the pretraining trial. Muscle [free carnitine] was lower (\( P < 0.05 \)) during exercise compared with rest in both trials, and muscle [acetyl carnitine] was higher (\( P < 0.05 \)) throughout exercise compared with the respective rest value in both trials (Table 1). In addition, muscle acetyl carnitine was lower after 5 min of exercise posttraining compared with pretraining.

**Muscle Enzymes**

The maximal enzyme activities of AAT and citrate synthase increased from pretraining to posttraining (Fig. 4). There was a 36% increase (\( P < 0.05 \)) in AAT activity and a 32% increase (\( P < 0.05 \)) in citrate synthase activity posttraining.
Blood Glucose and Lactate

Blood [lactate] was lower (P < 0.05) during exercise in the postraining trial compared with pretraining, but there were no differences between trials in blood [glucose] (data not shown).

DISCUSSION

This is the first study to examine the effect of chronic endurance training on skeletal muscle TCAI metabolism in humans. The two major findings from the present investigation were that 1) after training, the exercise-induced expansion of the muscle TCAI pool was attenuated, and cycle endurance capacity was not limited by a decrease in muscle [TCAI]; and 2) training did not alter the resting intramuscular concentrations of glutamate or alanine; however, the exercise-induced changes in these two amino acids were attenuated, which is consistent with lower net flux through AAT and anaplerotic entry of carbon into the TCA cycle.

Relationship Between Muscle TCAI Expansion and Aerobic Energy Provision During Exercise

It is well established that regular endurance exercise induces major adaptations in skeletal muscle, including an increase in mitochondrial content and respiratory control sensitivity (16). As a consequence, exercise performed at the same work intensity induces less metabolic disturbance and is characterized by a lower rate of muscle glycogen utilization, lactate accumulation, and phosphocreatine utilization. These training-induced metabolic adaptations were demonstrated in the present study, as well as an increased VO$_2$ peak and citrate synthase maximal activity. In addition to the well-established link between mitochondrial content and the capacity to perform prolonged submaximal exercise (16), it has been suggested that the size of the muscle TCAI pool during exercise plays a regulatory role in oxidative energy delivery and directly affects endurance capacity (21, 25–27). For example, in a recent review, Wagenmakers (26) stated that “changes in the size of the muscle pool of some amino acids and in amino acid metabolism play an important role in the establishment and maintenance of a high concentration of tricarboxylic acid (TCA)-cycle intermediates and via this mechanism in the maintenance of a high aerobic capacity during prolonged exercise.” One interpretation of the theory that links changes in

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**Table 1. Muscle metabolite data**

<table>
<thead>
<tr>
<th></th>
<th>Pretraining</th>
<th>Posttraining</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rest 5 min</td>
<td>EndEx1</td>
</tr>
<tr>
<td>PCR</td>
<td>97.7 ± 2.2</td>
<td>56.0 ± 5.0†</td>
</tr>
<tr>
<td>Cr</td>
<td>35.5 ± 2.5</td>
<td>77.1 ± 4.0†</td>
</tr>
<tr>
<td>Glycogen</td>
<td>405.3 ± 16.7</td>
<td>345.0 ± 22.4</td>
</tr>
<tr>
<td>Lactate</td>
<td>4.4 ± 0.5</td>
<td>56.4 ± 6.5†</td>
</tr>
<tr>
<td>ATP</td>
<td>25.3 ± 0.4</td>
<td>26.6 ± 0.5</td>
</tr>
<tr>
<td>Pyruvate</td>
<td>0.18 ± 0.03</td>
<td>0.63 ± 0.03†</td>
</tr>
<tr>
<td>Malate</td>
<td>0.02 ± 0.03</td>
<td>2.82 ± 0.13†</td>
</tr>
<tr>
<td>Fumarate</td>
<td>0.07 ± 0.01</td>
<td>0.86 ± 0.05†</td>
</tr>
<tr>
<td>Citrate</td>
<td>0.25 ± 0.03</td>
<td>0.45 ± 0.04†</td>
</tr>
<tr>
<td>Isocitrate</td>
<td>0.06 ± 0.01</td>
<td>0.16 ± 0.01†</td>
</tr>
<tr>
<td>Alanine</td>
<td>6.9 ± 0.4</td>
<td>12.5 ± 0.5†</td>
</tr>
<tr>
<td>Glutamate</td>
<td>11.2 ± 0.8</td>
<td>3.5 ± 0.4†</td>
</tr>
<tr>
<td>Free CoA</td>
<td>81.4 ± 7.8</td>
<td>68.8 ± 9.6</td>
</tr>
<tr>
<td>Acetylarnitine</td>
<td>2.5 ± 0.6</td>
<td>13.7 ± 1.6†</td>
</tr>
<tr>
<td>Carnitine</td>
<td>13.2 ± 1.5</td>
<td>4.9 ± 1.1†</td>
</tr>
</tbody>
</table>

Values are means ± SE in mmol/kg dry wt, except free CoA in μmol/kg dry wt; n = 8, except pyruvate where n = 6, and glycogen where n = 7, because of limited muscle extract. Cr, creatines; PCR, phosphocreatine. *P < 0.05 vs. pretraining at same time point. †P < 0.05 vs. rest during same trial. ‡P < 0.05 vs. End Ex1 during pretraining trial. EndEx1 and EndEx2, point of exhaustion during pre- and postraining trials, respectively.

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Fig. 2. Net change in muscle concentration of glutamate and alanine from rest to 5 min of exercise, before and after training. Values are means ± SE in mmol/kg dry wt (n = 8). *P < 0.05 vs. Pre.

Fig. 3. Muscle concentration of acetyl CoA at rest and during exercise, before and after training. Values are means ± SE in μmol/kg dry wt (n = 8). +P < 0.05 vs. rest during same trial.
[TCAI] during exercise with the capacity for oxidative metabolism (21, 25–27) is that a given concentration of TCAI is required to sustain a given rate of oxidative phosphorylation during prolonged exercise. Our data are clearly at odds with this line of reasoning because the same power output (and presumably rate of oxidative ATP provision) was maintained after training despite a ~50% decrease in the muscle TCAI pool. Moreover, the [TCAI] at EndEx1 (i.e., the time point that coincided with exhaustion during the pretraining trials) was not different after training (Fig. 1), and yet all subjects were able to continue cycling for at least another 30 min (mean improvement over pretraining trial: 49 ± 4 min).

It must be emphasized that the regulation of TCA cycle flux is extremely complex (28), and the potential for changes in [TCAI] to play a regulatory role in muscle energetics cannot simply be dismissed on the basis of the present findings. Indeed, one could argue that, after training, the sensitivity of mitochondrial respiration to [TCAI] is increased. This line of reasoning is analogous to the concept of altered ADP sensitivity in the control of respiration after endurance training, i.e., smaller increases in free [ADP] are required to sustain a given oxygen uptake. Just as it would be erroneous to conclude that ADP is unrelated to aerobic energy provision, the present findings do not rule out the potential for changes in TCAI to play a role in oxidative metabolism. Moreover, the precise factors that regulate TCA cycle flux may vary depending on the metabolic situation, and the relative importance of key intramitochondrial parameters such as the ATP/ADP and NAD+/NADH ratios can be influenced by the absolute concentrations of specific TCAI (28). It is also possible that a “rearrangement” of TCAI may occur (for example, the relative increase in [citrate] and decrease in [malate] seen during exercise after training in the present study) to maintain a given TCA cycle flux. Nonetheless, the present results clearly demonstrate that, after aerobic training, fatigue during prolonged exercise was unrelated to a decrease in the total muscle pool of TCAI. In addition, exercise capacity did not appear to be limited by substrate availability for the TCA cycle because the concentration of muscle acetyl-CoA during exercise in the posttraining trial was similar to the value associated with fatigue during the pretraining trial (Fig. 3).

Fig. 4. Maximal activity of muscle citrate synthase and alanine aminotransferase, measured in resting biopsy samples before and after training. Values are means ± SE in mmol·kg wet wt⁻¹·min⁻¹ (n = 8). *P < 0.05 vs. Pre.

Effect of Training on Alanine Aminotransferase, Glutamate, and Alanine

We observed an increase in the maximal activity of AAT after training, which is consistent with the findings of a previous training study (5) and also cross-sectional data showing that the activity of muscle AAT is higher in trained compared with untrained individuals (1). However, in spite of the higher maximal activity of this enzyme after training, the exercise-stimulated flux through AAT appeared to be reduced. This was evidenced by smaller net changes in the concentrations of muscle glutamate and alanine after training and reduced TCAI expansion. One potential explanation for a reduced rate of AAT flux is a reduction in pyruvate availability after training because the concentration of pyruvate during exercise tends to fluctuate around the Michaelis constant of AAT for pyruvate (0.3 mM) (18). In the present study, muscle [pyruvate] after 5 min of exercise was not different between trials; however, this static concentration provides little insight regarding actual fluxes during the initial few minutes of exercise. The fact that muscle glycogenolysis and lactate accumulation were markedly attenuated suggests that the rate of pyruvate availability may have been reduced during the initial minutes of exercise posttraining. Another consideration is that the analytic techniques employed in the present study do not permit the subcellular resolution of enzyme activities or metabolite concentrations. A particularly noteworthy finding by Ji and colleagues (17) was that endurance-trained rats have higher mitochondrial but not cytoplasmic fractions of AAT compared with sedentary control animals. Thus it is plausible that in the present study there may have been spatial differences with respect to the training-induced adaptations in metabolite fluxes and maximal enzyme activities.

Finally, training did not alter resting concentrations of muscle glutamate or alanine, which are an important substrate and product, respectively, for the AAT reaction. This is the first study to examine the effect of chronic endurance training on the concentrations of any amino acids in human muscle, and our data contrast with the results of a cross-sectional study conducted by Graham et al. (12). In that study, the muscle concentrations of glutamate and alanine were reported to be ~30 and ~20% higher, respectively, in a group of endurance-trained subjects compared with age-matched sedentary controls. Henriksson (14) also reported that trained subjects tended to have higher muscle concentrations of certain amino acids, including glutamate. With respect to the discrepancy between studies, it is possible that 7 wk of endurance training is simply not a sufficient stimulus to induce changes in the resting amino acid profile. Alternatively, there may have been individual differences in the groups of trained and untrained subjects examined in previous studies (12, 14) that contributed to the reported differences in muscle amino acid concentrations. One possible explanation relates to variation in muscle fiber composition: there are marked differences in the concentrations of several free amino acids between various muscles in the rat hindlimb (24); however, differences between human muscle fiber types appear less pronounced (9). Moreover, one might expect that endurance-trained individuals would have a higher proportion of type I fibers, but, somewhat paradoxically, Essen-Gustavsson and Blomstrand (9) reported higher concentrations of glutamate and alanine in type II fibers. Finally, as with
any study involving repeated muscle biopsy sampling, a limitation of the present work involves potential differences in fiber type or the extent of fiber recruitment at a given sampling point during exercise.

In summary, the results from the present study demonstrated that the contraction-induced increase in muscle [TCAI] was lower after 7 wk of aerobic training. The reduction in [TCAI] was consistent with lower net flux through the AAT reaction at the start of exercise, even though the maximal activity of this enzyme was increased after training. Training did not alter the resting concentrations of muscle glutamate and alanine. However, the net changes in these two amino acids were reduced during exercise, which is consistent with reduced anaplerotic carbon entry into the TCA cycle. Despite the blunted rise in [TCAI] after training, exercise capacity was markedly improved and thus there was a clear dissociation between the size of the [TCAI] pool, the capacity for oxidative energy delivery, and endurance exercise performance. The present findings do not rule out the potential for changes in TCAI to play a role in oxidative metabolism during exercise. However, our results clearly demonstrate that, after aerobic training, cycle endurance capacity is not limited by a decrease in the muscle TCAI pool.

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GRANTS

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