J Appl Physiol 105: 575–580, 2008.
First published May 15, 2008; doi:10.1152/japplphysiol.01129.2007.

Progressive recruitment of muscle fibers is not necessary for the slow component of $\dot{V}O_2$ kinetics

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Zoladz JA, Gladden LB, Hogan MC, Nieckarz Z, Grassi B. Progressive recruitment of muscle fibers is not necessary for the slow component of $\dot{V}O_2$ kinetics. *J Appl Physiol* 105: 575–580, 2008. First published May 15, 2008; doi:10.1152/japplphysiol.01129.2007.—The "slow component" of O_2 uptake ($\dot{V}O_2$) kinetics during constant-load heavy-intensity exercise is traditionally thought to derive from a progressive recruitment of muscle fibers. In this study, which represents a reanalysis of data taken from a previous study by our group (Grassi B, Hogan MC, Greenhaff PL, Hamann JJ, Kelley KM, Aschenbach WG, Constantin-Teodosiu D, Gladden LB. *J Physiol* 538: 195–207, 2002) we evaluated the presence of a slow component-like response in the isolated dog gastrocnemius in situ ($n = 6$) during 4 min of contractions at ~60–70% of peak $\dot{V}O_2$. In this preparation all muscle fibers are maximally activated by electrical stimulation from the beginning of the contraction period, and no progressive recruitment of fibers is possible. Muscle $\dot{V}O_2$ was calculated as blood flow multiplied by arteriovenous O_2 content difference. The muscle fatigued (force decreased by ~20–25%) during contractions. Kinetics of adjustment were evaluated for *1*) $\dot{V}O_2$, uncorrected for force development; *2*) $\dot{V}O_2$ normalized for peak force; *3*) $\dot{V}O_2$ normalized for force-time integral. A slow component-like response, described in only one muscle out of six when uncorrected $\dot{V}O_2$ was considered, was observed in all muscles when $\dot{V}O_2$/peak force and $\dot{V}O_2$/force-time were considered. The amplitude of the slow component-like response, expressed as a fraction of the total response, was higher for $\dot{V}O_2$/peak force (0.18 ± 0.06, means ± SE) and for $\dot{V}O_2$/force-time (0.22 ± 0.05) compared with uncorrected $\dot{V}O_2$ (0.04 ± 0.04). A progressive recruitment of muscle fibers may not be necessary for the development of the slow component of $\dot{V}O_2$ kinetics, which may be caused by the metabolic factors that induce muscle fatigue and, as a consequence, reduce the efficiency of muscle contractions.

skeletal muscle bioenergetics

DURING VOLUNTARY constant-load exercise in humans a steady-state of O_2 uptake ($\dot{V}O_2$) is attainable only for moderate-intensity exercise (for review, see Ref. 38), carried out below the so-called lactate threshold (LT). Above LT, after a rapid monoexponential increase ("fundamental," or phase II component of the kinetics), there is a further increase in $\dot{V}O_2$ (phase III, or "slow" component; 7, 17, 23, 38) that, during very heavy exercise [above "critical power" (38)], may approach maximal O_2 uptake ($\dot{V}O_{2\,max}$), with exhaustion ensuing at or soon after $\dot{V}O_{2\,max}$ is reached (24). The slow component of $\dot{V}O_2$ kinetics is not exclusive to dynamic exercise. Vøllestad et al. (36), for example, described a slow component of leg $\dot{V}O_2$ kinetics in humans during repeated isometric contractions of the quadriceps muscle. While the factors responsible for the slow component of $\dot{V}O_2$ kinetics are still debated (7, 17, 38, 40), it has been demonstrated that the "excess" $\dot{V}O_2$ associated with the slow component mainly derives from the exercising muscles (25). Traditionally, the slow component of $\dot{V}O_2$ kinetics is thought to be caused at least partly by a progressive recruitment, as a function of time, of aerobically less-efficient type II fibers (17) as heavy exercise proceeds and the initially recruited fibers become fatigued (5, 7, 17, 38, 40). According to some evidence, mainly obtained from animal studies, oxidative metabolism in type II fibers is characterized by a lower efficiency compared with type I fibers (4), which would explain the "excess $\dot{V}O_2$," with respect to the constant external power output, associated with the $\dot{V}O_2$ slow component.

In previous studies (10, 12) on the isolated dog gastrocnemius muscle preparation in situ (33) we occasionally reported a slow component of $\dot{V}O_2$ kinetics during electrically induced contractions corresponding to submaximal metabolic requirements. Considering that, in our model, all muscle fibers are maximally activated by electrical stimulation from the very beginning of the contraction period, this was a rather surprising observation, apparently in contradiction with the traditional concept of the slow component mentioned above. In our studies (10, 12), however, we did not attempt to interpret the occasionally observed slow component. Moreover, we neglected the fact that the adopted contraction paradigm was not a constant-load protocol, because the muscle fatigued during the contraction period and the developed force significantly decreased as a function of time. The association between a falling force output and a constant $\dot{V}O_2$ would indicate a reduced efficiency of oxidative metabolism, a process similar to that thought to be responsible for the slow component of $\dot{V}O_2$ kinetics during constant-load exercise in humans.

In the present study, which represents a reanalysis of data taken from one of our previous papers (10), we hypothesized that after normalizing the $\dot{V}O_2$ values per unit of force produced, the observed $\dot{V}O_2$ kinetics would be different from those originally reported. More specifically, a slow component-like response of $\dot{V}O_2$ kinetics would appear consistently, in the presence of a maximal activation of all muscle fibers from the beginning of the contraction period. The results would

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allow insights into the issue of whether a progressive recruitment of type II fibers is required for the development of a reduced efficiency of muscle contraction associated with the slow component of $\dot{V}O_2$ kinetics.

METHODS

The original study was conducted with approval of the Institutional Animal Care and Use Committee of Auburn University, Auburn, Alabama, where the experiments were performed. The methods were previously described in detail in the original publication (10) on which the present study is based. What follows is a general description of the experimental protocol, measurements, and data analysis. The present analysis deals only with the "Control" condition (i.e., the conditions in which no drugs were used) of the study, conducted on six adult mongrel dogs.

The gastrocnemius-plantaris-flexor digitorum superficialis muscle complex (for convenience referred to as "gastrocnemius") preparation (33) was used (left leg). Arterial and venous circulations to and from the muscle were surgically isolated. Blood flow ($\dot{Q}$) was measured by an ultrasound flow probe (6NRB440, Transonic Systems) positioned in the popliteal vein draining the muscle. The arterial circulation to the gastrocnemius was isolated by ligating all vessels from the femoral and popliteal artery that did not enter the gastrocnemius. The sciatic nerve was exposed and isolated near the gastrocnemius. To evoke muscle contractions, the nerve was stimulated by supramaximal square pulses of 4.0–6.0 V amplitude and 0.2-ms duration (Grass S48 stimulator). Isometric tetanic contractions were triggered by stimulation with trains of stimuli (4–6 V, 200-ms duration, 50-Hz frequency) at a rate of 2 contractions/3 s. On the basis of studies of peak $\dot{V}O_2$ in this model (1, 19), this stimulation pattern should elicit ~60–70% of peak $\dot{V}O_2$. The investigated metabolic transition was therefore a rest-to-submaximal (4 min) transition. Force was measured by an isometric myograph. For each contraction, peak force and the integral of the force vs. time tracing were determined (see Fig. 1). At the end of the experiments the dogs were killed with an overdose of pentobarbital sodium and injection of saturated KCl.

Muscle biopsies were obtained by superficial excision of muscle pieces with a scalpel, at rest and during the last 15 s of the contraction period. Biopsy samples were immediately frozen in liquid nitrogen. Adenosine triphosphate (ATP), phosphocreatine (PCr), and lactate concentrations were determined according to Harris et al. (14). Muscle hydrogen ion concentration was estimated according to Sahlin et al. (30). Free adenosine diphosphate (ADP_{free}) concentration was calculated according to Kemp et al. (20).

Samples of arterial blood entering the muscle and of venous blood from the popliteal vein were drawn anaerobically. Arterial samples were taken at rest, before the contractions and immediately after the contraction periods. A polyethylene tube was threaded into the popliteal vein cannula to the point where the vein exited the gastrocnemius. This allowed collection of venous blood immediately draining from the muscle. Venous samples were taken at rest (~10 s before the onset of contractions), every 5–7 s during the first 75 s of contractions, and every 30–45 s thereafter until the end of the contraction period. Blood samples were immediately stored in ice and analyzed at 37°C for P_{O_2}, P_{CO_2}, and pH by a blood gas, pH analyzer (IL 1304, Instrumentation Laboratories), and for hemoglobin concentration ([Hb]) and percent saturation of Hb (SO_2, %) with a CO-oximeter (IL 282, Instrumentation Laboratories) set for dog blood.

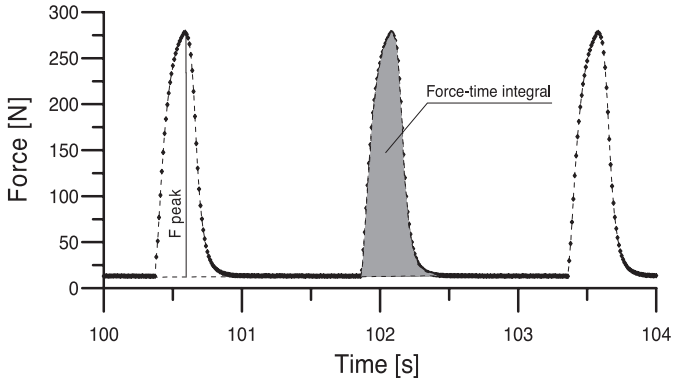

Fig. 1. For each contraction, peak force (F peak, see the arrow drawn for the first contraction) and force-time integral (see the shaded area for the second contraction) were calculated. See METHODS for further details.

$\dot{V}O_2$ of the gastrocnemius was calculated by the Fick principle as $\dot{V}O_2 = \dot{Q}\cdot C(a\text{-}v)O_2$, where $C(a\text{-}v)O_2$ is the difference in O_2 concentration between arterial blood and venous blood. $\dot{V}O_2$ was calculated at discrete time intervals corresponding to the timing of the blood samples. Whereas in the original study only uncorrected $\dot{V}O_2$ (ml·100 $g^{-1}\cdot min^{-1}$) was considered, in the present study $\dot{V}O_2$ data were also normalized per unit of peak force, that is per N/100 g (thus, they were expressed as ml $O_2\cdot min^{-1}\cdot N^{-1}$) as well as per unit of force-time integral, that is per N·100 $g^{-1}\cdot s$, yielding ml $O_2\cdot min^{-1}\cdot(N\cdot s)^{-1}$. Peak force and the force-time integral were measured/calculated at the times corresponding to the blood samplings. Both variables were used for the normalization, since muscle fatigue is usually associated with both a decrease in peak force and with a slower relaxation phase. Thus the force-time integral might better represent the energy demand of force development by the muscle. Data were subsequently fitted by two equations, i.e., by *equation 1* and by *equation 2*. *Equation 1* was of the type:

$$y(t) = yBAS + Af[1 - e^{-(t-TDf)/\tau f}] \quad (1)$$

In this equation, yBAS indicates the baseline value obtained at rest before contraction onset, A*f* indicates the amplitude between *y*BAS and the steady-state value at the end of the contraction period, TD*f* the time delay and τf the time constant of the function. The suffix *f* indicates that these parameters relate to the "fundamental" component of the $\dot{V}O_2$ kinetics (38).

Equation 2 was of the type:

$$y(t) = yBAS + Af[1 - e^{-(t-TDf)/\tau f}] + As[1 - e^{-(t-TDs)/\tau s}] \quad (2)$$

In this equation, A*s,* TD*s*, and τs indicate, respectively, the amplitude, the time delay, and the time constant of the slow component-like response of the kinetics (38). The equation that best fitted the experimental data was determined by *F* test (see below). That is to say, when *equation 2* provided a better fit of the data, a slow component-like response of the $\dot{V}O_2$ kinetics was present, superimposed on the fundamental component. The slow component-like response, however, did not always follow an exponential function, being sometimes linearly related to the time of exercise; moreover, its τs values appear devoid of physiological significance. The actual amplitude of the slow component-like response (A′*s*) was estimated as the difference between the last $\dot{V}O_2$ value obtained during the contraction period and the asymptotic value of the primary component. The relative contribution of the slow component-like response to the total amplitude of the response was also calculated (13, 29).

Statistical analysis. Values were expressed as means ± SE. To determine the statistical significance of differences between two means, a paired Student's *t*-test (2-tailed) was performed. To determine the statistical significance of differences among more than two means, a repeated-measures analysis of variance was performed. A Tukey's post hoc test was used to discriminate where significant differences occurred. Data fitting by exponential functions was performed by an iterative least-squares approach. Comparison between fittings with different exponential models was done via *F* test. The level of significance was set at $P < 0.05$. Data fitting and statistical analyses were carried out by using a commercially available software package (GraphPad Prism 4, GraphPad Software).

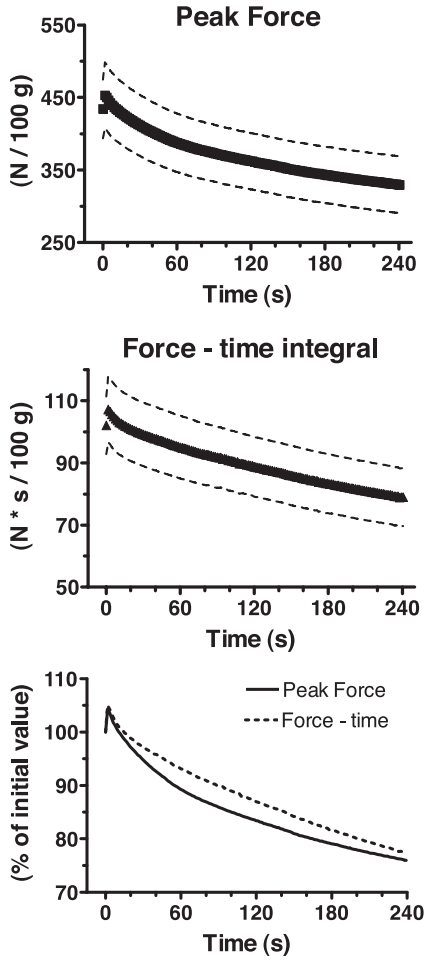

Fig. 2. Mean (±SE) (dashed lines) values of peak force and of force-time are given at *top* and *middle*. At *bottom*, mean values of the 2 variables are expressed as a percentage of the values determined during the first contraction. See RESULTS for further details.

RESULTS

Mean (±SE) values of peak force and of the force-time integral are given in Fig. 2, *top* and *middle*. Figure 2, *bottom*, shows mean values of the two variables expressed as a percentage of the values determined during the first contraction. For both variables, after a slight increase during the first four to five contractions, possibly attributable to a "staircase" effect, a progressive decrease was observed, indicating fatigue of the contracting muscles. Although at the end of the contraction period the decreases of the two variables were very similar (75.2 ± 4.1% of initial values for peak force vs. 76.5 ± 3.5% for the force-time integral, no significant difference), their time courses were slightly different (see Fig. 2, *bottom*). Thus $\dot{V}O_2$ values were "normalized" to both variables for comparison.

$\dot{V}O_2$ kinetics analysis. Individual values of uncorrected $\dot{V}O_2$ (Fig. 3, *left*), $\dot{V}O_2$/peak force (Fig. 3, *middle*), and $\dot{V}O_2$/force time integral (Fig. 3, *right*) are shown in Fig. 3 as a function of the time of contractions. When uncorrected $\dot{V}O_2$ was considered, *equation 2* provided a better fit for the data (that is, a slow component-like response of $\dot{V}O_2$ kinetics was identified) in only one of the six experiments. On the other hand, a slow component-like response was identified in five of six experiments for $\dot{V}O_2$/peak force, and in all six experiments for $\dot{V}O_2$/force-time integral. The absence of a slow component-like response when uncorrected $\dot{V}O_2$ was considered, and the presence of a substantial slow component-like response when $\dot{V}O_2$/peak force and $\dot{V}O_2$/force-time integral were presented, is also shown in Fig. 4, in which mean (±SE) data are shown.

The amplitudes of the slow component-like response, expressed as a fraction of the total amplitudes of the $\dot{V}O_2$ responses, were significantly higher for $\dot{V}O_2$/peak force (0.18 ± 0.06) and for $\dot{V}O_2$/force-time integral (0.22 ± 0.05) compared with uncorrected $\dot{V}O_2$ (0.04 ± 0.04).

As for kinetics parameters related to the "fundamental" component of the $\dot{V}O_2$ kinetics, no significant differences were observed, for both the time delay (5.3 ± 0.5 s for uncorrected $\dot{V}O_2$, 5.1 ± 0.4 s for $\dot{V}O_2$/peak force, 5.6 ± 0.5 s for $\dot{V}O_2$/force-time integral) and the time-constant (15.7 ± 1.0 s for uncorrected $\dot{V}O_2$, 18.2 ± 1.7 s for $\dot{V}O_2$/peak force, 15.6 ± 1.4 s for $\dot{V}O_2$/force-time integral) between the three sets of data.

DISCUSSION

In the original study (10) from which the data of the present analysis are derived, we occasionally observed a slow component of $\dot{V}O_2$ kinetics in maximally activated (by electrical stimulation) canine muscles in situ during 4-min contractions at ~60–70% of peak $\dot{V}O_2$. In that study, the muscle fatigued during the contraction period. In the present analysis, a slow component-like response of $\dot{V}O_2$ kinetics became a constant feature when the original $\dot{V}O_2$ values were normalized per unit of peak force or force-time. A critical issue of the present analysis is the following: can we consider what we observed, after normalizing $\dot{V}O_2$ per unit of force, a true slow component of $\dot{V}O_2$ kinetics? In strict terms no. During voluntary exercise in humans, a constant power output is maintained by increasing $\dot{V}O_2$; in our model, on the other hand, in the presence of a maximally activated muscle we observed a constant $\dot{V}O_2$ in the presence of a falling force output, that is a sort of "mirror image" of the slow component. For this reason in the present study we are mostly using the term "slow component-like response." Both observations have a common denominator, however, that is a decreased efficiency of muscle contraction. The novel observation deriving from the present study is that this reduced efficiency of muscle contraction, putative mechanism responsible for the slow component, is not necessarily related to a progressive recruitment of muscle fibers.

Both Barstow et al. (3) and Pringle et al. (26) observed that the amplitude of the slow component of $\dot{V}O_2$ kinetics is positively correlated with the percentage of type II fibers. Progressive recruitment of type II muscle fibers has been traditionally supported as the mechanism responsible for the "excess $\dot{V}O_2$" and the slow component of $\dot{V}O_2$ kinetics (5, 17, 38). According to this hypothesis, during constant-load heavy intensity exercise, some of the motor units recruited first may fatigue, eliciting a progressive recruitment of new motor units, which are probably composed more and more of type II muscle fibers. The evidence most cited in favor of this hypothesis, mainly obtained in animal studies, is that oxidative metabolism in type II fibers is characterized by a lower efficiency compared with type I fibers (4), which would explain the excess $\dot{V}O_2$ responsible for the $\dot{V}O_2$ slow component. Very few studies, however, have actually compared metabolic efficiency in type

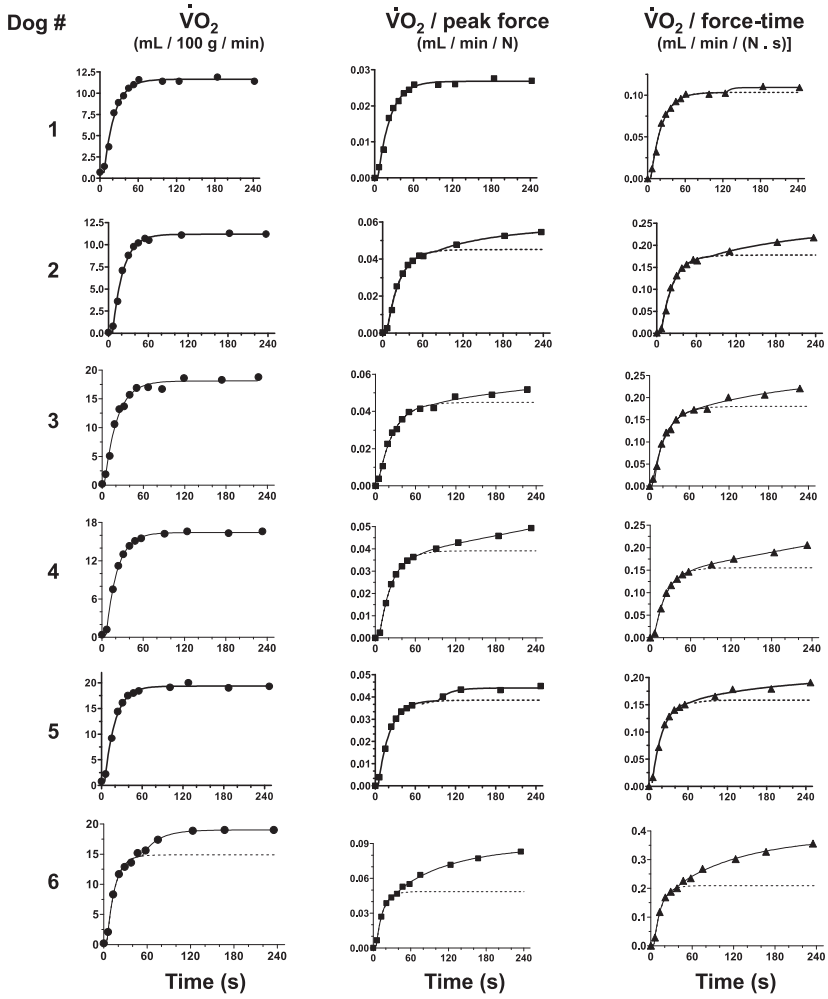

Fig. 3. Individual values of uncorrected $\dot{V}O_2$ (*left*), $\dot{V}O_2$/peak force (*middle*), and $\dot{V}O_2$/force-time integral (*right*) as a function of the time of contractions. The dashed lines indicate the asymptote of the fundamental component of the kinetics. See *$\dot{V}O_2$ kinetics analysis* for further details.

I and II fibers of human muscle. According to He et al. (15) peak thermodynamic efficiency is not significantly different between type I and type II or type IIA/IIX fibers, although peak efficiency is obtained in type I fibers at significantly lower load and speed of shortening. Evidence in favor and against a progressive recruitment of type II fibers as the mechanism responsible for the slow component of $\dot{V}O_2$ kinetics has been recently discussed in the review by Jones et al. (17). The newly recruited fibers may not necessarily be type II. According to Krustrup et al. (22) during exercise at 80% of $\dot{V}O_{2\,max}$, in humans, both type I and type II fibers were recruited from the onset of exercise, and additional fibers (of both types) were recruited with time in temporal association with the development of the slow component of $\dot{V}O_2$ kinetics. Although a progressive recruitment of additional fibers likely occurs in other experimental models (22, 35), it was not possible in our model, in which all fibers were maximally activated from the onset of contractions. Nevertheless, after we normalized $\dot{V}O_2$ per unit of developed force or force-time, a slow component-like response of skeletal muscle $\dot{V}O_2$ kinetics became evident. Our results do not rule out the possibility that during voluntary exercise in exercising humans the slow component may be at least in part explained by progressive motor unit recruitment, but demonstrate that, at least in our isolated canine muscle preparation in situ, a slow component-like response of $\dot{V}O_2$ kinetics occurs even in the absence of a progressive recruitment of fibers.

As an alternative explanation for the slow component, the fatigued muscle could become less efficient as a direct consequence of fatigue itself (39). This phenomenon could explain the occurrence of the slow component independently from a sequential recruitment of fibers. The increased $\dot{V}O_2$/force (or force-time) ratio, and the associated slow component of $\dot{V}O_2$ kinetics, could evolve from factors related to the effects of fatigue on the initially recruited type II fibers (17). The muscles could become less efficient because they are approaching the metabolic characteristics of fatigue, such as a decrease in the Gibbs free energy of ATP hydrolysis, decreases in phosphocreatine and glycogen concentrations, as well as increases in $[H^+]$, [ADP], $[P_i]$, [IMP], $[NH_3]$, etc. (6, 31, 32, 37, 39). The slow component of $\dot{V}O_2$ kinetics, then, could be associated with (or be a consequence of) a lower level of "metabolic stability" (41). Good metabolic stability during rest-to-work transition in skeletal muscle means less decrease in [PCr] and in the cytosolic phosphorylation potential, as well as less increase in $[P_i]$, $[ADP_{free}]$, $[AMP_{free}]$, $[IMP_{free}]$ for a given increase in $\dot{V}O_2$ (41). In the present study the exercise-induced increase in muscle $\dot{V}O_2$, from 0.4 ± 0.1 ml $O_2 \cdot 100\ g^{-1} \cdot min^{-1}$ at rest to 16.1 ± 1.6 ml $O_2 \cdot 100\ g^{-1} \cdot min^{-1}$ at the end of exercise, was accompanied by essentially no changes in ATP concentration

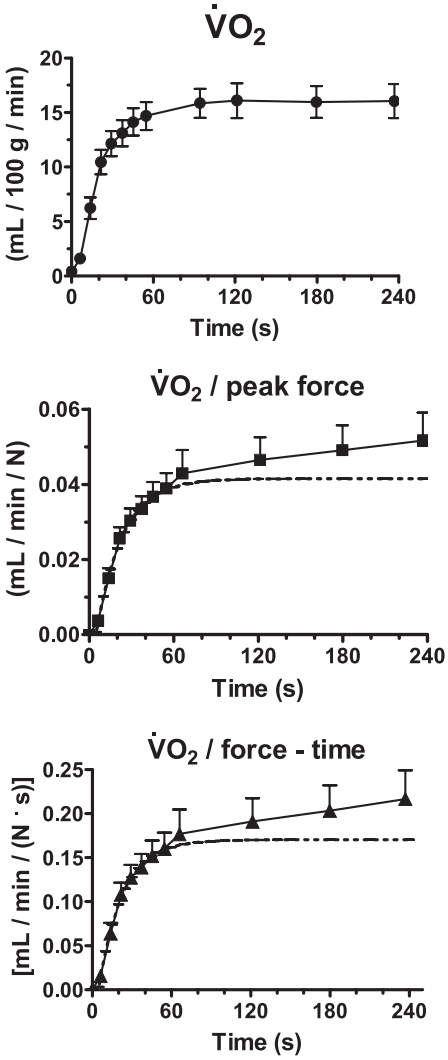

Fig. 4. Mean (±SE) values for uncorrected $\dot{V}O_2$ (*top*), $\dot{V}O_2$/peak force (*middle*), and $\dot{V}O_2$/force-time integral (*bottom*) as a function of the time of contractions. The dashed lines indicate the asymptote of the fundamental component of the kinetics. See *$\dot{V}O_2$ kinetics analysis* for further details.

(24.1 ± 1.0 vs. 23.6 ± 0.5 mmol/kg dry matter) and by a significant decrease in [PCr] (from 69.6 ± 3.8 to 41.7 ± 2.4 mmol/kg dry matter) (10). Interestingly, the 40-fold increase in $\dot{V}O_2$ was accompanied by only ~2.5-fold increase in the calculated [ADP_{free}], from 39.8 ± 1.0 μM at rest to 94.2 ± 9.4 μM at the end of the contraction period. Small relative increases in [ADP_{free}], in the presence of much greater relative increases in $\dot{V}O_2$, are typical for well-trained fatigue-resistant oxidative muscles (see e.g., Ref. 2, 16, 21, 41). In the present study, despite a relatively small disturbance in the muscle's metabolic stability, as suggested by the relatively small increase in [ADP_{free}], the magnitude of the slow component-like response of $\dot{V}O_2$ kinetics (after normalizing $\dot{V}O_2$ to force or force-time) was substantial, amounting to ~20–25% of the total $\dot{V}O_2$ response. This suggests that a slow component-like response of $\dot{V}O_2$ kinetics may occur also in muscles characterized by an elevated metabolic stability, in association with relatively small disturbances of the latter (41).

It has also been postulated that even a small decrease in the ΔG_{ATP} may affect the sarcoplasmic reticulum Ca^{2+} pump and prolong muscle relaxation time (18). This may lead to a rise in the resistance within the contractile machinery and contribute to the drop of muscle efficiency by increasing the internal work in the muscle (needing some extra ATP not used for the production of external mechanical power) and thus enhancement in the $\dot{V}O_2$/power output ratio (40). This concept would be in agreement with the growing body of evidence showing that the slow component in the $\dot{V}O_2$ kinetics is caused by a decreased efficiency of the contractile machinery (increase of the ATP/power output ratio) rather than by a decreased efficiency of the ATP production system (increase in the $\dot{V}O_2$/ATP ratio) (29, 40). According to Rossiter et al. (29), the slow component of $\dot{V}O_2$ kinetics is associated with a slow component of PCr kinetics, that is with an increased "phosphate cost" for force production, which would explain the reduced contractile efficiency.

Another possibility is that the reduced efficiency of muscle could result from the metabolic cost of recovery processes in fatigued fibers, which may contribute little, if any, to force or power output (forcing the muscle to recruit more motor units to keep force or power output constant). Despite a lack of force development, these fatigued fibers would consume O_2 for Ca^{2+} and Na^+/K^+ pump activities, as hypothesized by previous authors (17, 27).

It must be recognized that the experimental model we used presents some limitations, which have been discussed at length in previous papers (10), and mainly refer to the intrinsic invasiveness of the preparation and to the pattern of muscle activation (synchronous tetanic contractions), which is quite different from that encountered in cycling or running, although it is similar to other common exercise paradigms, such as repeated maximal handgrip contractions. In the present study, however, maximal activation of all muscle fibers from the onset of the contraction period represented an advantage, since it excluded the possibility of a progressive recruitment of fibers during the contraction period.

The concept of a constant ATP turnover rate ("error signal"), which is usually implied in $\dot{V}O_2$ kinetics analysis, may not hold true in our model, in which the ATP turnover rate may decrease as a consequence of the decreased force output. On the other hand, the ATP turnover rate may increase as a function of the increased ATP cost for force production associated with fatigue. The net results of these two phenomena, going in opposite directions, is difficult to estimate. An increased ATP cost for force or power production, in the presence of a constant power output (that is, an increased error signal), would also apply to exercising humans, and is considered one of the causes (or the cause) of the slow components of PCr and $\dot{V}O_2$ kinetics.

Interestingly, our findings (that is, a substantially constant $\dot{V}O_2$ in the presence of a falling force output) appear compatible with observations in exercising humans. Stoudemire et al. (34), for example, observed that, to keep the rate of perceived exertion (and pulmonary $\dot{V}O_2$) constant from 15 to 30 min of exercise, subjects running on a treadmill progressively reduced the running speed. In that study, running speed corresponded, at the beginning of the exercise bout, to that associated during a preliminary incremental exercise to a blood lactate of 4 mM. Ribeiro et al. (28) reported that power output had to be reduced by ~15%, during 40 min of cycle ergometer exercise, to keep $\dot{V}O_2$ constant at ~80% of $\dot{V}O_{2max}$.

In conclusion, in isolated canine muscle in situ, during contractions corresponding to 60–70% of $\dot{V}O_2$ peak and in the absence of a progressive recruitment of muscle fibers, we observed a clear $\dot{V}O_2$ slow component-like response after $\dot{V}O_2$ data were normalized per unit of produced force. Thus a progressive recruitment of muscle fibers is not necessary for the development of the slow component of $\dot{V}O_2$ kinetics. We postulate that the slow component is caused by the metabolic factors that induce muscle fatigue and, as a consequence, reduce the efficiency of muscle contractions.

GRANTS

This study was supported in part by Agentia Spatiala Italiana-Osteoporosie Atrofia Muscolare Contract I/007/06/0 (Workpackage 1B-32) and by North Atlantic Treaty Organization Collaborative Linkage Grant 979220. J. A. Zoladz was also supported by funding from the Akademia Wychowania Fizycznego-Krakow for statutory research (2007).

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