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Relationship in Simulation between Oxygen Deficit and Oxygen Uptake in Decrement-load Exercise Starting from Low Exercise Intensity

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Abstract The purpose of the present study was to determine by simulation whether oxygen deficit kinetics in decrement-load exercise (DLE) starting from a low exercise intensity is related to the oxygen uptake ($\dot{V}o_2$) kinetics. In this simulation, work rate in DLE was separated into steps that were regarded as constant-load exercises (CLEs). It was assumed that $\dot{V}o_2$ kinetics behaved exponentially at the onset and offset of each CLE, respectively. $\dot{V}o_2$ at the onset of CLEs increases at the same time and becomes a recovery phase step-by-step corresponding to the decrement of work rate. The sum of $\dot{V}o_2$ values at the onset of CLEs at a given time (nt-$\dot{V}o_2$) corresponds to $\dot{V}o_2$ excluding oxygen debt in DLE. The sum of $\dot{V}o_2$ values at the offset of CLEs at a given time (dt- $\dot{V}o_2$) corresponds to $\dot{V}o_2$ related to oxygen debt in DLE. The total of net- and dt-$\dot{V}o_2$ values is equivalent to $\dot{V}o_2$ actually observed in DLE (gs-$\dot{V}o_2$). As the oxygen requirement level is a steady-state value of $\dot{V}o_2$ in CLE, the oxygen deficit level can be obtained by subtracting $\dot{V}o_2$ at the onset of CLE from the steady-state value. The oxygen deficit level at a given time was added in all CLEs. This is oxygen deficit per unit time (df-$\dot{V}o_2$). Oxygen debt and oxygen deficit were calculated by integrating df-$\dot{V}o_2$ and dt-$\dot{V}o_2$ from the start of exercise to a given time, respectively. Gs-$\dot{V}o_2$ increased, reached a peak, and decreased linearly until the end of the DLE. Oxygen deficit increased rapidly and showed a steady state. Oxygen debt increased linearly after a time lapse. The difference between oxygen deficit and oxygen debt changed like gs-$\dot{V}o_2$ kinetics. Therefore, it is concluded that if we consider the repayment of oxygen debt in the oxygen deficit in DLE, the kinetics of the oxygen deficit becomes similar to gs-$\dot{V}o_2$ kinetics in the simulation. *J Physiol Anthropol 22 (1): 1–5, 2003* http://www.jstage.jst.go.jp/en/

Keywords: simulation, decrement-load exercise, oxygen uptake, oxygen debt, oxygen deficit

Introduction

Whipp et al. (1992) reported the following interesting results regarding oxygen uptake ($\dot{V}o_2$) kinetics in decrement-load exercise (DLE). $\dot{V}o_2$ exponentially increased and decreased linearly until the end of the DLE. $\dot{V}o_2$ during the period of linear decrease was higher in DLE than in incremental-load exercise (ILE) at the same work rates. This higher $\dot{V}o_2$ is thought to be associated with the repayment of oxygen debt during DLE. The rate of decrement of $\dot{V}o_2$ against the decrement of work rate was 14 ml/min/watts when initial workload was started from the maximal level and 10 ml/min/watts in case of the exercise intensity below the anaerobic threshold. This higher decrement rate is suggested to be associated with oxygen cost of lactate. Thus, $\dot{V}o_2$ kinetics in DLE includes oxygen debt.

When DLE is performed after ILE, the oxygen deficit produced in the ILE is repaid in the DLE (Miyamoto and Niizeki, 1992; Yano et al., 2000). In this decrement phase, $\dot{V}o_2$ decreases linearly after exponential decrease. In DLE in which the work load is reduced from the start of exercise, an oxygen deft kinetics may also be produced from the early phase of the exercise. However, the kinetics of oxygen debt in DLE, especially that in the early phase of exercise, is still not clear.

Oxygen deficit is produced at the onset of DLE. In exercise of low intensity, the main energy source of oxygen deficit is phosphocreachine (CrP). It is hypothesized that the decrease in CrP induces an increase in $\dot{V}o_2$ (Mahler, 1985). This hypothesis has been confirmed in constant-load exercise (CLE) below the anaerobic threshold (Rossiter et al., 1999). However, since oxygen deficit is produced only at the onset of DLE, decrement of $\dot{V}o_2$ that appears in the latter phase of DLE cannot be explained only by the oxygen deficit. Oxygen debt should be taken into consideration.

In the present study, $\dot{V}o_2$ kinetics, oxygen debt and oxygen deficit in DLE were estimated by computer simulation since measurement of actual instant oxygen debt is not possible at present. We examined in the simulation whether the difference between oxygen deficit and oxygen debt kinetics in decrement-load exercise (DLE) starting from a low exercise intensity is related to $\dot{V}o_2$ kinetics.

Methods

Description of the model

Work rates in DLE were separated into several CLEs of which the durations increase step by step (See Fig. 1 for example.). In the present study, DLE starting from work rate of 120 watts was simulated. The work rate of 120 watts was divided into 32 steps (n=32). Therefore, the work rate of each CLE was 3.75 watts. The initial duration of CLE was 15 sec and its duration increased by 15 sec in each step (Dn) (for example, D_1=15 sec, D_2=30 sec, and so on). $\dot{V}o_2$ for one watt (gain) was assumed to increase by 10 ml/min/watt (Henson et al., 1989). Therefore, the steady-state value of $\dot{V}o_2$ in each step (An) was 37.5 ml/min. The time constant (τ) was assumed to be 0.5 min or 1.0 min. These values are almost within the range reported for low exercise intensity (Rossiter et al., 1999; Ozyener et al., 2001).

$\dot{V}o_2$ ($E\dot{V}o_2n$) kinetics at the onset of each CLE was estimated using the following equation (Whipp et al., 1981) (See Fig. 1 for example.):

$$E\dot{V}o_2(t)n = An\cdot(1-\exp(-t/\tau)),$$
$$\text{then } 0\le t\le Dn, \text{ and } Dn=0.25\cdot n. \quad (1)$$
$$\text{If } t>Dn, \text{ then}$$
$$E\dot{V}o_2(t)n=0.$$

Here, n is the number of steps, An is the amplitude of the system (37.5 ml/min), t is time, and τ is the time constant of the system (0.5 or 1.0 min). Eq. (1) is valid from the start to the end of each CLE.

The sum of $E\dot{V}o_2(t)n$ values in CLEs from step one to step 32 at a given time becomes net oxygen uptake (nt-$\dot{V}o_2$) in DLE. That is,

$$Nt\text{-}\dot{V}o_2(t)=\Sigma[E\dot{V}o_2(t)n]. \quad (2)$$

Note the condition of Eq. (1). When a given time is more than the durations of some CLEs, the values of $\dot{V}o_2(t)$ in those CLEs become zero.

In the present simulation, $\dot{V}o_2$ in exercise and recovery periods was assumed to be symmetric so that oxygen deficit can coincide with oxygen debt. Therefore, the following equation can be used to estimate recovery $\dot{V}o_2$ ($R\dot{V}o_2$) (See Fig. 1 for example.):

$$R\dot{V}o_2(t)n = Bn - Bn\cdot(1-\exp(-(t-Dn)/\tau))$$
$$= Bn\cdot\exp(-(t-Dn)/\tau),$$
$$\text{then } t>Dn \text{ and } Dn=0.25\cdot n. \quad (3)$$
$$\text{If } t<Dn, \text{ then}$$
$$R\dot{V}o_2(t)n=0.$$

Here, Bn is the value of $E\dot{V}o_2n$ at the end of exercise in each step, and τ is the time constant of the system. The value of τ in the recovery period is the same as that during exercise. Bn is the value in Eq. (1) when time is equal to Dn (t=Dn). That is,

$$Bn=An\cdot(1-\exp(-Dn/\tau)). \quad (4)$$

Note that Bn is not always equal to An because An is a steady-state value of CLE.

The sum of $R\dot{V}o_2n$ values in CLEs from step one to step 32 at a given time becomes oxygen debt per unit time (dt-$\dot{V}o_2$). That is,

$$Dt\text{-}\dot{V}o_2(t)=\Sigma[R\dot{V}o_2(t)n]. \quad (5)$$

Note the condition of Eq. (3).

Gross oxygen uptake (gs-$\dot{V}o_2$) is the sum of nt-$\dot{V}o_2$ and dt-$\dot{V}o_2$. That is,

$$Gs\text{-}\dot{V}o_2(t)=\text{Eq. (2)}+\text{Eq. (5)}. \quad (6)$$

Oxygen deficit per unit time (df-$\dot{V}o_2$) is given by sum of values of the difference between An and Eq. (1) from step one

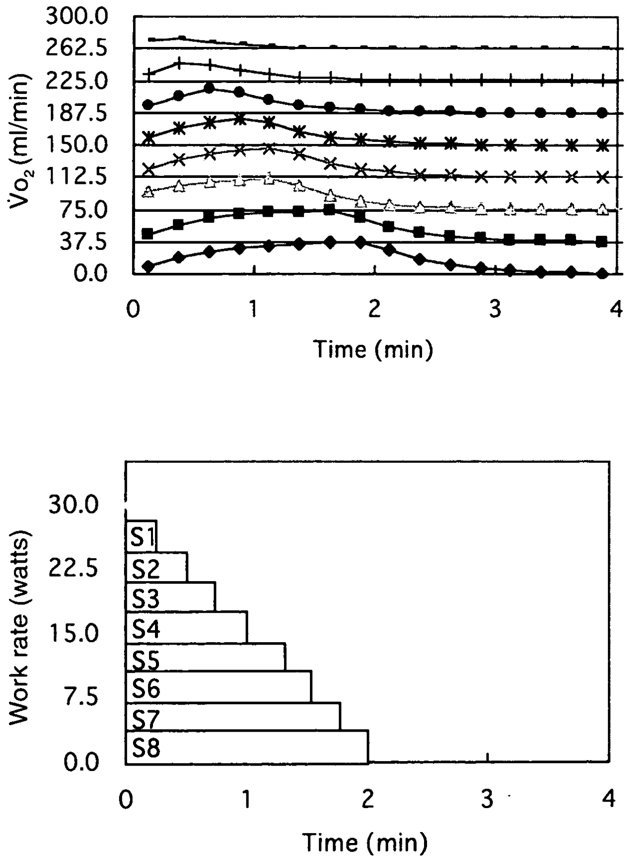

Fig. 1 The lower panel shows the work rate in decrement-load exercise starting from 30 watts with a decreasing rate of 15 watts. There are eight steps. These steps are divided into each constant-load exercise (CLE). Each CLE finishes step by step from the top to the bottom. At that time, oxygen uptake ($\dot{V}o_2$) increases at the onset of each CLE and decreases at the offset of each CLE (upper panel).

to step 32 at a given time, since An is the oxygen requirement level in each CLE.

$$\text{Df-}\dot{V}o_2(t)=\Sigma(An-E\dot{V}o_2(t)n). \qquad (7)$$

Oxygen deficit and oxygen debt were obtained by summing the product of their unit values (dt-$\dot{V}o_2$ and df-$\dot{V}o_2$) and duration (Δt) with elapse of time.

$$O_2\ \text{deficit}=\Sigma(\text{dt-}\dot{V}o_2\cdot\Delta t), \qquad (8)$$

$$O_2\ \text{debt}=\Sigma(\text{df-}\dot{V}o_2\cdot\Delta t). \qquad (9)$$

Data were outputted at 0.25-min intervals after an initial datum was located in 0.125 min from the starting point. That is,

$$t=(k/4)-0.125, \qquad (10)$$

where k is a natural number.

Results

Factors consisting in $\dot{V}o_2$ kinetics determined by the time constant of 0.5 min are shown in Fig. 2. Gs-$\dot{V}o_2$ increased, reached a peak, and decreased linearly until the end of exercise. The values of nt-$\dot{V}o_2$ were lower than those of gs-$\dot{V}o_2$ but tended to show the same behavior as those of gs-$\dot{V}o_2$. The rate of decrement in $\dot{V}o_2$ in the latter period of DLE was 150 ml/min/min in both gs- and nt-$\dot{V}o_2$. When the linear phase of nt-$\dot{V}o_2$ was extrapolated toward the beginning or end of the exercise, their values were estimated to be 1200 ml/min at the beginning of the exercise and zero ml/min at the end of the exercise. Df-$\dot{V}o_2$ exponentially decreased and became nearly zero. Dt-$\dot{V}o_2$ increased soon after the start of the exercise and showed a steady state.

In Figs. 3 and 4, factors consisting in $\dot{V}o_2$ kinetics in DLE are shown in the cases in which time constants were 0.5 and 1.0 min. Df-$\dot{V}o_2$ in the case of a slow time constant showed higher values than those in the case of a fast time constant at the same time and became nearly zero at 4 min. Dt-$\dot{V}o_2$ in the case of a slow time constant showed a slow response and steady state. The steady-state values were around 75 ml/min in

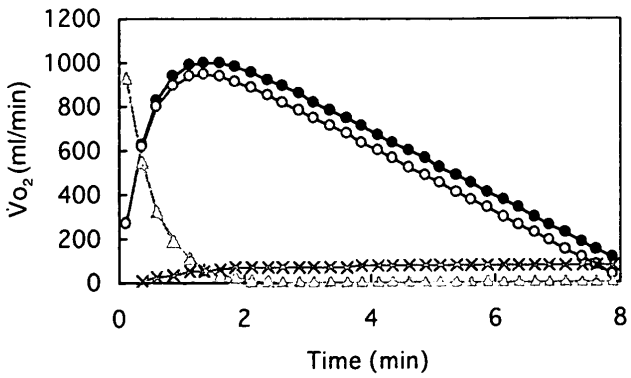

Fig. 2 Results of simulation with a time constant of 0.5 min at the onset and offset of constant-load exercises. Gross oxygen uptake (gs-$\dot{V}o_2$: ●), net oxygen uptake (nt-$\dot{V}o_2$: ○), deficit oxygen uptake (dt-$\dot{V}o_2$: ×) and debt oxygen uptake (dt-$\dot{V}o_2$: ▲) are shown.

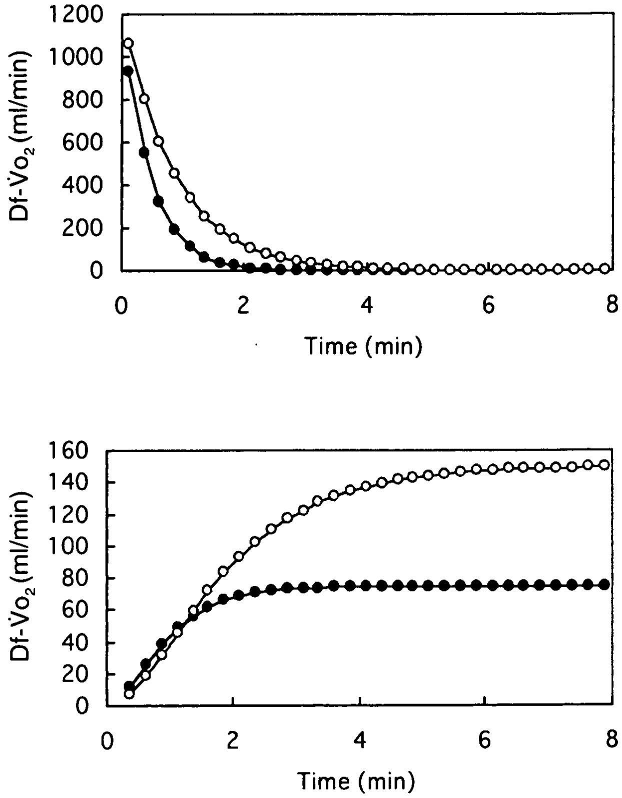

Fig. 3 Deficit oxygen uptake (df-$\dot{V}o_2$) and debt oxygen uptake (dt-$\dot{V}o_2$) estimated by time constants of 0.5 (●) and 1.0 (○) min.

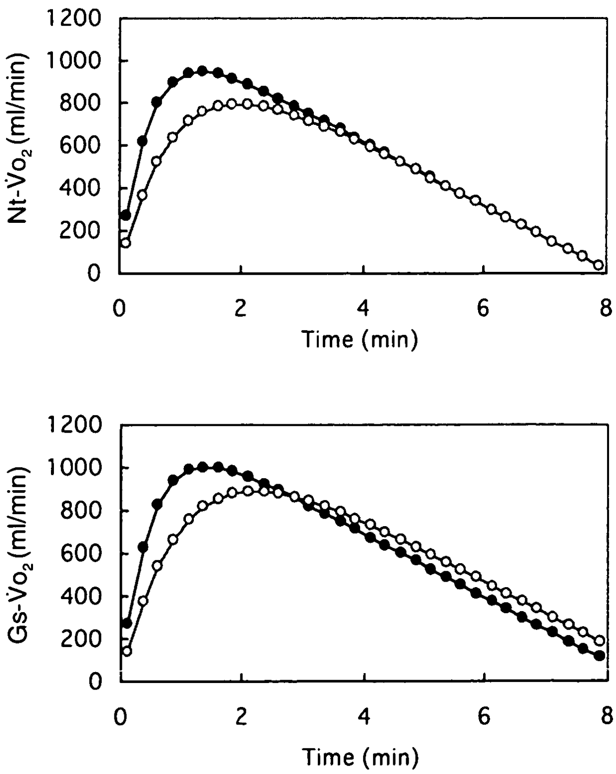

Fig. 4 Gross oxygen uptake (gs-$\dot{V}o_2$) and net oxygen uptake (nt-$\dot{V}o_2$) estimated by time constants of 0.5 (●) and 1.0 (○) min.

the case of a fast time constant and around 150 ml/min in the case of a slow time constant. Nt-$\dot{V}o_2$ in the case of a slow time constant showed a slower response than that in the case of a fast time constant, but there was no difference between the latter values of nt-$\dot{V}o_2$ in the two cases. Gs-$\dot{V}o_2$ in the case of a slow time constant showed a slower response but higher value in the latter part of the exercise than those in the case of a fast time constant. This slower response is derived from the slower response of nt-$\dot{V}o_2$, and the higher value in the latter part of the exercise is derived from the higher value of dt-$\dot{V}o_2$. A peak of gs-$\dot{V}o_2$ appeared at 1.5 min and its value was around 1000 ml/min. In the case of a slow time constant, a peak appeared at 2 min and its value was around 900 ml/min. After the peak, gs-$\dot{V}o_2$ decreased at a rate of 150 ml/min/min in both cases of slow and fast time constants.

The differences between oxygen deficit and oxygen debt are shown in Fig. 5. The oxygen deficit increased at the onset of the exercise and showed a steady state. The oxygen debt increased linearly after a time lapse. The difference in the case of a fast time constant reached a peak at 1.5 min and its value was around 500 ml. In the case of a slow time constant, the peak appeared at 2.0 min and its value was around 900 ml.

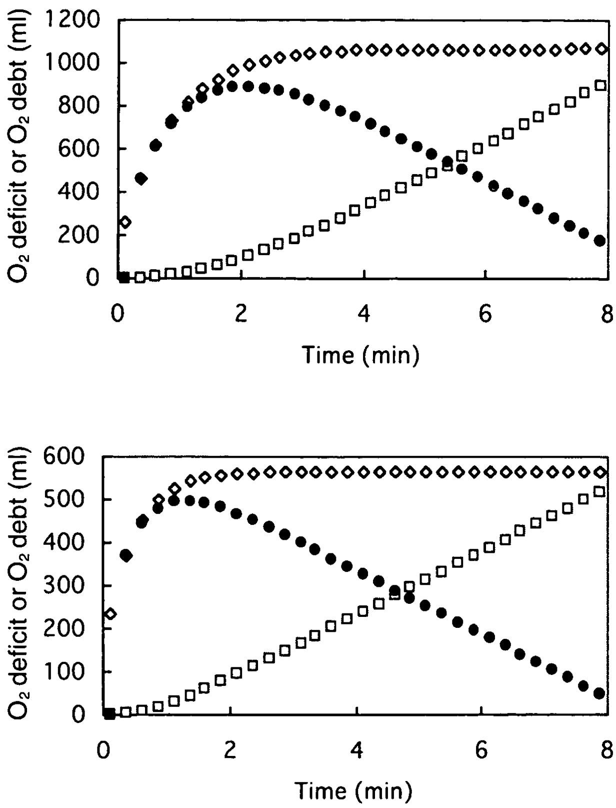

Fig. 5 O_2 deficit (◇) and O_2 debt (□) are shown at a given time in decrement-load exercise. The difference between O2 deficit and O2 debt (●) is shown at a given time. The upper panel shows the results of simulation with a time constant of 1.0 min, and the lower panel shows the results of simulation with a time constant of 0.5 min.

Discussion

$\dot{V}o_2$ is known to increase due to the increase in cardiac output and the change in oxygen content in mixed venous blood before the blood in active muscle reaches the lung (Whipp et al., 1982; Casaburi et al., 1989). This phenomenon occurs not only at the onset of exercise but also at the offset of exercise. At the onset of DLE this phenomenon occurs in all CLEs at the same time in the present simulation. However, as CLEs finishes step by step, it is difficult to introduce the time delays at the offset of exercises. Therefore, the simulation in the present study was carried out for a simple case of no time delay. Time constants of 1.0 and 0.5 min were used in the simulation to express the kinetics of $\dot{V}o_2$, because we considered that the actual phenomena occurred within this range (Rossiter et al., 1999; Ozyener et al., 2001).

Actually measurements of $\dot{V}o_2$ kinetics at the same work load as that used in the present study have been reported (Yano et al., 2003). The $\dot{V}o_2$ exponentially increased after the cardiodynamic phase, reached a peak at around 2 min, and decreased linearly until the end of the exercise. Its peak value was about 1000 ml/min. The time when the peak appeared almost coincides to that in the present simulation if the time delay existing in actual measurement is taken into consideration. The peak value coincides with the results of simulation. However, the reported rate of decrement in $\dot{V}o_2$ in the latter part of DLE is higher than that in the simulation. This may be due to the effect of transport from active muscle to the lung. Thus, the present simulation is an accurate reflection of actual measurement.

In the present study, it was assumed that $\dot{V}o_2$ increased by 10 ml/min due to the rise in one watt of work rate (Hanson et al., 1989). Therefore, the oxygen requirement level in DLE should be 1200 ml/min at the beginning of the exercise and should become zero at the end of the exercise by a decrement rate of 150 ml/min per minute. Nt-$\dot{V}o_2$ is affected by the response speed of $\dot{V}o_2$ assumed in CLEs at the onset of DLE. Later, it becomes the oxygen requirement level because oxygen debt is not included in nt-$\dot{V}o_2$. This was confirmed by the results of our simulation. Thus, there is no conflict between the theory assumed in CLEs and resultant behavior of $\dot{V}o_2$ in DLE concerning oxygen requirement level.

In the present simulation, dt-$\dot{V}o_2$ was produced soon after the onset of exercise. Therefore, there was a period of overlap with df-$\dot{V}o_2$. Such a situation has never been considered. However, there are two possible explanations for this.

One could be explained by the dynamic equilibrium in the chemical reaction related to oxygen deficit or debt. Oxygen deficit is supplied by energy sources from oxygen store, early lactate formation and CrP breakdown (Di Prampero and Ferretti, 1999). However, early lactate and oxygen store do not provide so much energy in low exercise intensity such as in the present study. Therefore, CrP is considered to be the main source of oxygen deficit. The process of CrP breakdown is as follows:

$$CrP = P + Cr,$$

where P is phosphate and Cr is creatine. The speed of the chemical reaction in the right direction corresponds to df-$\dot{V}o_2$, and the speed of the chemical reaction in the left direction corresponds to dt-$\dot{V}o_2$. The speed of the reaction in the right direction is greater than that in the left direction at the onset of DLE. This difference is instant oxygen deficit, which can be observed in actual measurement. Df-$\dot{V}o_2$ becomes zero in the latter part of DLE. Then Dt-$\dot{V}o_2$ can be observed in actual measurement.

The other could be explained by the parallel transaction in each muscle unit. The muscle units recruited for work is released corresponding to the decrement of workload. As a result, oxygen debt can be repaid. Meanwhile in the other muscle units engaged in work, oxygen deficit is produced until $\dot{V}o_2$ reaches a steady state.

It has been reported that oxygen deficit is associated with oxygen uptake by the following equation (Whipp et al., 1981):

$$\dot{V}o_2 = O_2 \text{ deficit}/\tau$$

When the time constant is 1.0 min, oxygen deficit is coincident with oxygen uptake. In the case of a time constant of 0.5 min, half of the oxygen deficit corresponds to $\dot{V}o_2$. This relationship brings in a hypothesis that CrP is a factor controlling oxygen uptake. From the results of the present simulation, it is concluded that the hypothesis is confirmed in DLE if the repayment of oxygen debt is taken into consideration on the oxygen deficit.

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