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THE COST OF THE OXYGEN DEBT AT HIGH ALTITUDE

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It is known that the oxygen consumption during the steady state of exercise does not show any significant difference whether the muscular activity is performed at sea level or at high altitude. But, as far as we are aware, the total amount of oxygen used for a given amount of work has never been measured as a function of altitude and acclimatization. This is the purpose of a study, the first step of which is reported here.

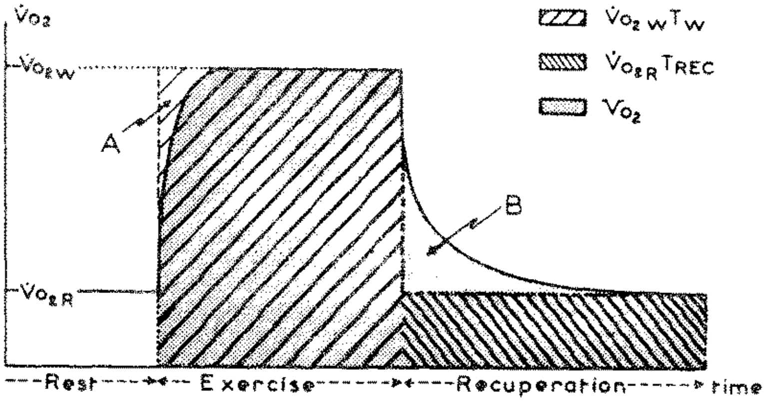

Fig. 1. Schematic representation of the oxygen consumption as a function of time, before, during and after a moderate exercise. The cost of the oxygen debt ($V_{O_2\,(B-A)}$) is represented by the difference between the two areas A and B.

Principle

The total volume of oxygen, which is necessary for the exercise and the following recovery, can be written as being the sum of 3 different components (Fig. 1).

$$V_{O_2} = \dot{V}_{O_{2W}} TW + \dot{V}_{O_{2R}} T_{REC} + V_{O_{2(B-A)}}$$

V_{O_2}	Volume of oxygen utilised during exercise and recovery.
$\dot{V}_{O_{2W}}$	Oxygen uptake during the steady state of the exercise.
$\dot{V}_{O_{2R}}$	Oxygen uptake at rest before the exercise and after the end of the recovery period.
$V_{O_{2(B-A)}}$	Cost of oxygen debt, *i.e.*, difference between the oxygen debt (area A on Fig. 1) and its repayment (area B on the same figure).

T_W Duration of the exercise.

T_{REC} Duration of the recovery, that is the time necessary for returning to the normal metabolic state.

In the preceding equation, all terms but the last – the cost of the oxygen debt – can be directly measured.

Technique

Four lowlanders (30 years old) have been studied both at 50 m (Paris, France) and at 3,750 m (La Paz, Bolivia) after residing there for 30 to 60 days. They exercised the upper limbs by raising 15 times per minute a weight placed in front of them to a height of 51 cm. In different experiments, the weight was 2, 4, 6, 8 and 10 kg.

The exercise was maintained until a steady state was reached, plus 3 min. for gas sampling. This type of mild exertion ($\dot{V}_{O_{2W}}$ never exceeded 5 times $\dot{V}_{O_{2R}}$) was chosen because it was neither too heavy nor too long; it allowed a true steady state and avoided a long time for complete recovery. Arm exercise was prefered to leg because it yielded a larger oxygen debt for equal oxygen uptake (Bevegård *et al.*, 1966).

All through the experiment, the ventilation ($\dot{V}_E$), the respiratory (f) and heart (F) rates were recorded. The oxygen consumption, the carbon dioxide production and the

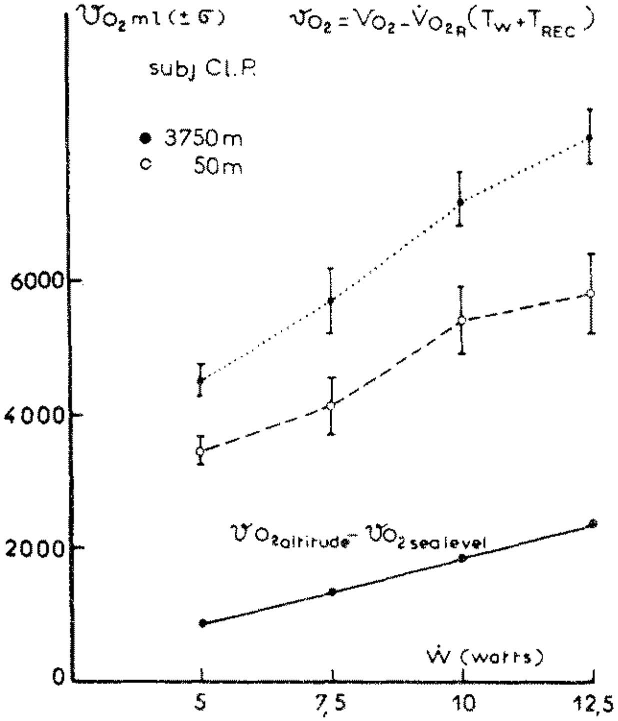

Fig. 2. Volume of oxygen used during an exercise (V_{O_2}) as a function of the mechanical power (Ẇ) at low and high altitude. At the bottom is shown the difference between the two upper curves. The resting oxygen consumption during the times of exercise and recovery ($\dot{V}_{O_{2R}}(T_W + T_{REC})$) has been deducted.

respiratory quotient (R) were determined at rest before the exercise, during the steady state of exercise and after recovery. These later values had to match the figures obtained at rest within 5%. The over-all oxygen uptake (V_{O_2}), and carbon dioxide production (V_{CO_2}) and respiratory quotient V_{CO_2}/V_{O_2} (R. glob.) were measured by collecting the whole expired gas from the beginning of exercise to the end of recovery.

The steady state was defined using f, F and $\dot{V}_E$ as criteria. Afterwards this had to be confirmed by steady values of $\dot{V}_{O_2w}$ and $\dot{V}_{CO_2w}$ and metabolic values of R; otherwise the experiment was disregarded. The same criteria were used by comparison with the resting values to determine and confirm the end of the recovery.

Results (Table I)

TABLE I

Main data obtained by comparing moderate muscular exercises performed by lowlanders at 50 and 3,750 m.

Altitude m	$\dot{W}$ watts	$\dot{V}_E$	$\dot{V}_{O_2}$	$\dot{V}_{CO_2}$	f	F	R		$V_{O_2 (B.A.)}$ ml/kg
		ml/mn/m² ± σ			mn⁻¹ ± σ		inst. ± σ	glob.	
3 750	Rest	6 214 ± 937	148 ± 23	121 ± 19	16.4 ± 3.0	91.1 ± 9.4	.82 ± .08	—	—
	2.5	10 154 ± 1 706	266 ± 57	218 ± 21	15	99.3 ± 9.4	.80 ± .06	.84 ± .05	3.9 ± 2.0
	5.0	11 880 ± 534	311 ± 12	273 ± 24	15	103.9 ± 9.1	.88 ± .07	.85 ± .08	11.4 ± 2.2
	7.5	14 080 ± 2 097	345 ± 44	333 ± 56	15	106.8 ± 5.7	.96 ± .06	.84 ± .05	11.7 ± 2.8
	10.0	17 379 ± 2 864	443 ± 43	409 ± 73	15	121.2 ± 12.1	.92 ± .10	.87 ± .08	13.9 ± 3.6
	12.5	18 653 ± 3 000	474 ± 60	437 ± 63	15	120.4 ± 12.4	.91 ± .06	.89 ± .08	15.3 ± 4.1
50	Rest	3 734 ± 1 143	128 ± 20	95 ± 18	14.3 ± 1.5	77.1 ± 7.6	.74 ± .08	—	—
	2.5	—	—	—	—	—	—	—	—
	5.0	7 614 ± 816	273 ± 44	229 ± 21	15	77.8 ± 6.5	.82 ± .10	.80 ± .06	3.5 ± 1.7
	7.5	9 951 ± 2 070	348 ± 39	313 ± 43	15	100.4 ± 8.1	.88 ± .08	.84 ± .08	4.5 ± 1.7
	10.0	11 271 ± 1 882	376 ± 40	347 ± 51	15	130.8 ± 12.1	.90 ± .05	.87 ± .02	11.4 ± 3.4
	12.5	13 679 ± 3 502	447 ± 53	426 ± 84	15	147.4 ± 24.3	.92 ± .09	.86 ± .08	11.9 ± 4.6

N.B.: During the exercise respiratory rate kept pace with the motion of the arms.

The weight of the subjects decreased during their stay at high altitude, hence neither bodyweights nor surface areas are the same in all experiments.

The total volume of oxygen utilised during an exercise and its recovery is definitely larger at high altitude (Fig. 2).

Looking at the preceding equation, this can be the result of a larger $\dot{V}_{O_{2R}}$, $\dot{V}_{O_{2W}}$ and/or $V_{O_2(B-A)}$.

1. $\dot{V}_{O_{2R}}$ In our series of experiments, resting values for $\dot{V}_{O_2}$ are slightly (20 ml/mn/m^2) but significantly ($p < 0.0005$) larger at high altitude than at sea level. Both sets of experiments were done in the same environmental conditions except for altitude and relative humidity of the air. Subjects had taken no food for 8 to 10 hrs, nevertheless the respiratory quotient at rest was found to be significantly ($p < 0.0005$) higher with altitude.

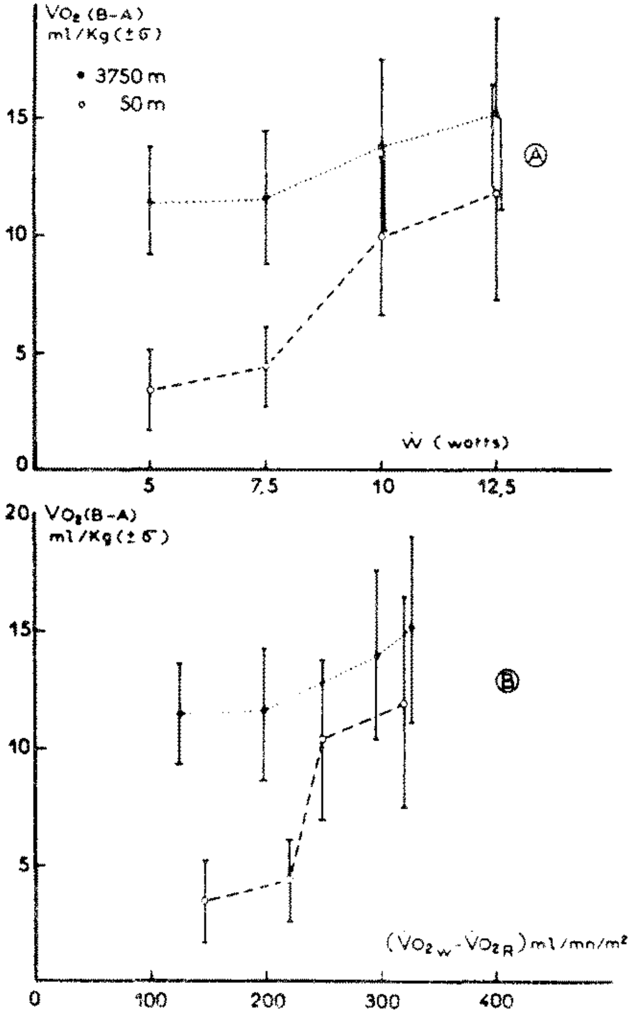

Fig. 3. Cost of oxygen debt ($V_{O_2(B-A)}$) as a function of:
A – The mechanical power ($\dot{W}$).
B – The physiological power ($\dot{V}_{O_{2W}} - \dot{V}_{O_{2R}}$), i.e.the increase of oxygen uptake.

2. $\dot V_{O_2W}$ — $\dot V_{O_2W}$ is also slightly but much less significantly higher in high altitude experiments: but, the values of net increase of oxygen uptake ($\dot V_{O_2W}$—$\dot V_{O_2R}$) are the same at both levels. That is to say, the increase in oxygen consumption due to the exercise is independant of the altitude.
3. $V_{O_2(B-A)}$ — The cost of the oxygen debt was found to be constantly and significantly higher at altitude, and the difference between sea level values increases with the power of exercise (Fig. 3).

If the total oxygen uptake for an exercise is larger at high altitude this is mainly due to a larger cost of the oxygen debt repayment. This can be expressed in terms of mechanical efficiency: the over-all efficiency is lower at high altitude; but the net efficiency is unaltered (Fig. 4).

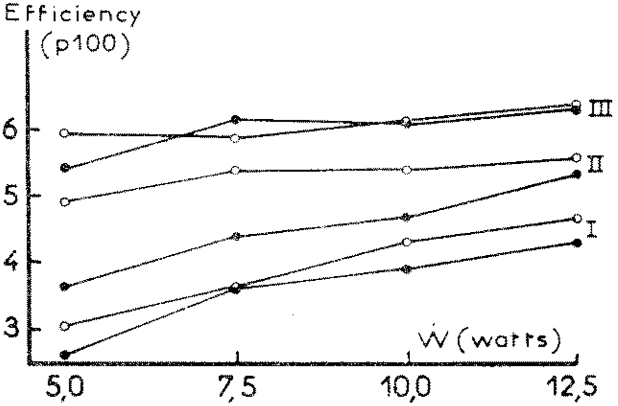

Fig. 4. Efficiency of muscular work as a function of mechanical power at high and low altitude.

I Rough efficiency: $\frac{\dot W}{a\dot V_{O_2W}}$

II Over-all efficiency: $\frac{\dot W}{a(V_{O_2}-\dot V_{O_2R})(T_W+T_{REC})}$

III Net efficiency: $\frac{\dot W}{a(\dot V_{O_2W}-\dot V_{O_2R})}$

(a: conversion factor)

Discussion

There is some disagreement in the literature about oxygen uptake at rest as a function of altitude. Some authors, reporting results of measurements made chiefly on natives and sojourners, found no significance difference (Hurtado *et al.*, 1956; Picon-Reategui, 1961; Rotta *et al.*, 1956; Valasquez, 1964); Chiodi (1957) gave higher values for newcomers than for natives or long term residents; Hultgren *et al.*, (1965) found an average of 154 ml 0_2/mn/m^2 at sea level; Gill and Pugh (1964) in a preliminary report stated that basal metabolism at 5,800 m was unaltered but after closer examination they came to the conclusion that there is a small but significant elevation of the oxygen uptake in basal conditions. This increase has been explained by the cost of ventilation, changes in environmental factors other than altitude and alimentary conditions. Part of difference might also be due to increase of heart rate;

Boicourt *et al.* (1966) have shown an increase in oxygen uptake at rest in patients with heart disease that could be related to a higher myocardial metabolism. In addition, besides a greater adrenal activity, some metabolic changes suggest an increase in thyroid activity (Surks, 1966) during exposure to high altitude. This would agree with the decrease of body weight (1.5 kg/month) without appetite impairment that we have noticed.

It seems that there is a general agreement that the oxygen debt is smaller in high altitude (Edwards, 1936; Hurtado *et al.*, 1956; Valasquez, 1964) although there are only a few cases reported concerning mild exercise performed with equal power at both levels. With the present experimental procedures we were not able to determine the actual value of the oxygen debt but only the difference between the debt and its repayment; however we noticed that the time of recovery was longer at altitude, as far as $\dot{V}_E$, f, $\dot{V}_{O_2}$, $\dot{V}_{CO_2}$ were concerned (mean time of recovery, in La Paz 14.4 mn, in Paris 8.1 mn).*

As far as we are aware, there are no data concerning the cost of oxygen debt repayment at altitude; taking the values of oxygen debt for exercises yielding the same oxygen consumption given by Duke *et al.*, (1965), repayment would be 30 to 35% greater than the debt at sea level, and 40 to 45% at 3,750 m. Although experimental conditions were quite different this figure might be compared with the values published by Coffmann and Gregg (1961) on ischemic heart muscle.

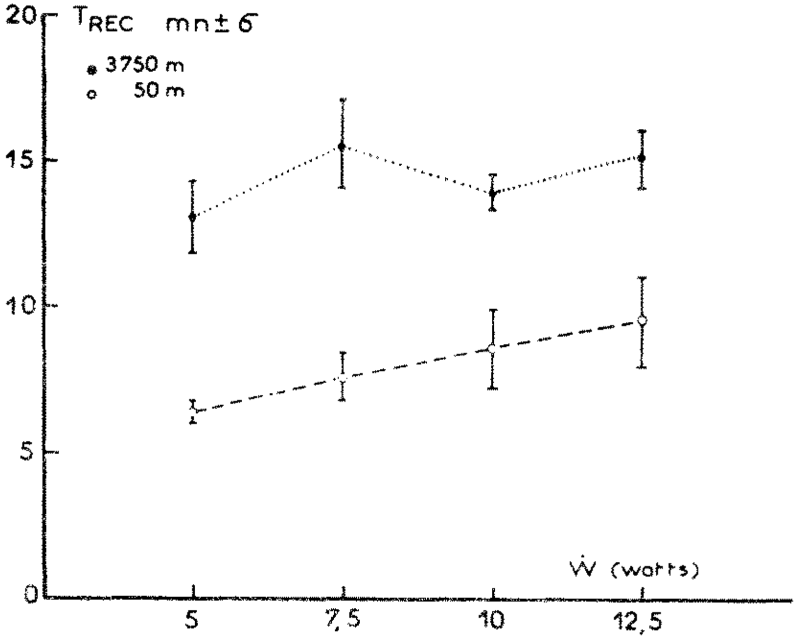

Fig. 5. Duration of post exercise recovery (T_{REC}) as a function of the mechanical power ($\dot{W}$) at high and low altitude.

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* This is in contrast with heart rate, which always returned faster to its control values and often with an undershoot (Figs. 5 and 6).

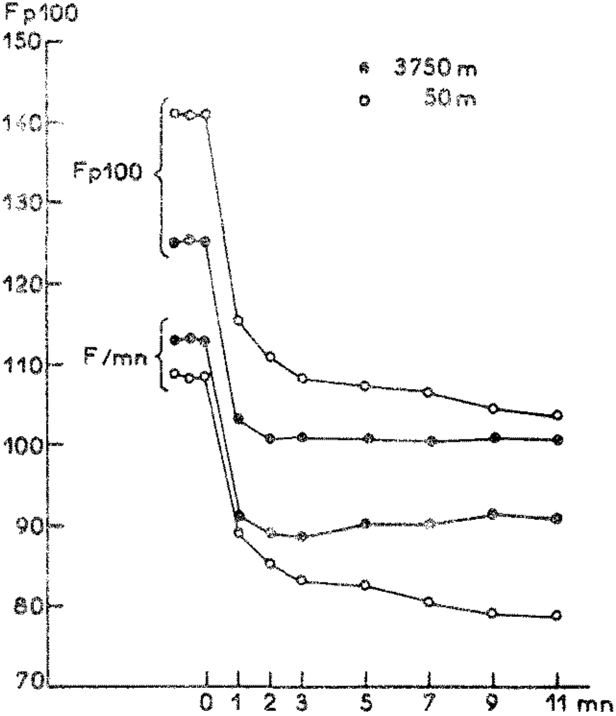

Fig. 6. Heart rate (F) as a function of time during the recovery at low and high altitude. (F is expressed both in percentage of resting values and in actual values).

In conclusion, at high altitude, at least in visitors, muscular work demands a greater amount of oxygen. This larger oxygen consumption does not appear during the exercise but occurs afterwards, during the recovery as a larger repayment of the oxygen debt.

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