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EFFECTS OF AIRFLOW LIMITATIONS AND TRAINING STATUS ON GAS EXCHANGE AND HEART RATE RECOVERY KINETICS IN ELDERLY SUBJECTS

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Abstract

To determine whether disease and training status results in different recovery kinetics of gas exchange and heart rate response in elderly subjects, 12 healthy control subjects, 18 patients with chronic obstructive pulmonary disease and 12 master athletes were examined during the five-minute recovery from maximal graded exercise. The recovery rate constants of oxygen uptake ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), ventilation ($\dot{V}_E$), and heart rate (HR) were fitted by a one-exponential model. Nonlinear regression showed that COPD exhibited a significantly slower recovery decay than CS for ($\dot{V}O_2$), ($\dot{V}CO_2$) and ($\dot{V}_E$), whereas HR recovery appeared to be unaffected by the disease status compared to controls. MA recovered faster than CS, except for ($\dot{V}_E$) recovery decay. We also demonstrated that the gas exchange and heart rate recovery kinetics were independent of maximal exercise work rate. We conclude that training generally improved the recovery responses in elderly subjects in contrast to the status of respiratory disease.

***Keywords**: oxygen uptake, carbon dioxide production, heart rate, ventilation, recovery, elderly subjects.*

Résumé

Pour déterminer si les états de maladie et d'entraînement induisent des réponses différentes dans les cinétiques de récupération des échanges gazeux et de la fréquence cardiaque chez des sujets âgés, un groupe de contrôle composé de 12 sujets sains, 18 patients atteints de maladie pulmonaire chronique obstructive et 12 athlètes vétérans ont été examinés durant les 5 minutes de récupération consécutives à un exercice graduel maximal. Pour déterminer les constantes de vitesse de récupération, les valeurs de la consommation d'oxygène ($\dot{V}O_2$), production du dioxyde de carbone ($\dot{V}CO_2$), ventilation ($\dot{V}_E$), fréquence cardiaque (FC) ont été ajustées à un modèle mono-exponentiel. La régression non linéaire a montré que les BPCO ont une récupération plus lente que le GC pour la $\dot{V}O_2$, $\dot{V}CO_2$ et $\dot{V}_E$, la FC apparaît ne pas être affectée par leur état de maladie. MA ont récupéré plus rapidement que GC, excepté pour la $\dot{V}_E$. Les constantes de vitesse de récupération des échanges gazeux et de la FC sont indépendantes de la puissance maximale de travail physique. Ces données suggèrent que l'entraînement améliore les réponses à la récupération chez les sujets âgés, contrairement à l'état de maladie respiratoire.

***Mots clés**: consommation d'oxygène, production de dioxyde de carbone, fréquence cardiaque, ventilation, récupération, sujets âgés.*

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ملخص

لتحديد ما إذا كان المرض وحالة التدريب ينتج عنها حالات استرجاع مختلفة للتبادل الغازي واستجابة نبضات القلب لدى الأفراد المسنين، تم استعمال مجموعة شاهدة تتكون من 12 فرد ذوي صحة جيدة، مجموعة ثانية تتكون من 18 مريض ذوي الانسداد الرئوي المزمن ومجموعة ثالثة تتكون من 12 رياضي مختص في المداومة ، لفحصهم أثناء الخمسة دقائق الأولى بعد الانتهاء من التمرين ذات الشدة القصوى. تم تكييف بيانات النسب الثابتة للاسترجاع من استنشاق الأكسجين وغاز ثاني أكسيد الكربون، التهوية ونبضات القلب بواسطة نموذج أسي. وقد يبين التراجع اللاخطي أن مرض الانسداد الرئوي المزمن أظهر استرجاع بطيء مقارنة بالمجموعة الشاهدة بالنسبة لحجم الأكسجين وناتج غاز ثاني أكسيد الكربون ونبضات القلب، في حين أن استرجاع نبضات القلب لم تتأثر بالحالة المرضية مقارنة بالمجموعة الشاهدة، وكانت عملية الاسترجاع لدى الرياضيين المسنين أسرع مما هو عليه لدى المجموعة الشاهدة ما عدا فيما يتعلق بالتهوية حيث كانت متماثلة بالنسبة للمجموعتين .

***الكلمات المفتاحية:** استرجاع من استنشاق الأكسجين وغاز ثاني أكسيد الكربون، نبضات القلب، التهوية، التبادل الغازي، الأفراد المسنين.*

Interpretation of exercise testing results is relatively standardized for patients and sedentary elderly subjects in terms of maximal and submaximal exercise [1]. However, little is known about the recovery process even if it is obvious from a clinical point of view that different patients or subjects show different recovery patterns [2,3].

The fast component of post-exercise $\dot{V}O_2$ recovery may be partly explained by the changes in PCr concentration after exercise cessation [4]. Patients with chronic obstructive pulmonary disease (COPD) have low concentrations of ATP and PCr in muscles [5] in contrast to elderly athletes (MA), who showed a lower Pi/PCr slope [6] compared with age-matched older subjects. In addition, COPD patients have a reduced aerobic capacity, hypercapnia [7], hyperventilation for a given load [8] and slower HR recovery [9] after a maximal graded exercise [9]. In contrast to the latter, MA show relative hypoventilation for a given absolute load [10] and lower HR during recovery [11]. These differences in metabolic and functional profile suggest that the regulation of gas exchange after exercise would be different among patients, sedentary subjects and master athletes and that disease and training status could affect the recovery kinetics.

Recently, Cohen-Solal *et al*. [12] showed in patients with chronic heart failure that recovery of all ventilatory variables is delayed in proportion to the severity of disease. In this study, the authors validated a simple clinical index to determine the $T_{1/2}$ (half time) of $\dot{V}O_2$ recovery that yielded information similar to $T_{1/2exp}$. In patients with COPD, Chick *et al.* [9] showed a different pattern of recovery in

comparison to a control group using the unpaired Student's *t*-test method. These authors did not precisely study the recovery kinetics of the physiological responses to exercise.

The aim of this study was therefore to 1) compare the recovery kinetics of $\dot{V}O_2$, $\dot{V}CO_2$, $\dot{V}_E$, and heart rate, and the associated decay constants after graded exercise in groups of elderly patients with chronic obstructive pulmonary disease, sedentary adults (CS) and elderly endurance-trained athletes (MA) by means of an exponential model, and 2) to validate a clinical tool by comparing the half time assessed by simple measurement ($T_{1/2}$) with the half time given by the exponential model ($T_{1/2exp}$) in COPD and trained athletes.

METHODS

Subjects

Eighteen male patients with chronic obstructive pulmonary disease (COPD) [58±2.4 yr], twelve male untrained control subjects (CS) [66 ± 1.6 yr] and twelve male endurance-trained master athletes (MA) [64 ± 1.6 yr (mean ± SE)] took part in this study. The physical characteristics of the subjects are presented in Table 1.

The eighteen patients with stable COPD, defined according to the criteria of the ATS [13], were recruited from our outpatient department of respiratory investigations. All patients were without exacerbation of their disease for at least six weeks prior to the study. Depending on their age, they had mild to moderate hypoxia [14]. Arterial blood gas analysis at rest showed that oxygen tension (PaO_2) was higher than 55 mmHg in all the COPD patients who were ex-smokers. Electrocardiograms showed normal sinus rhythms. Patients were excluded if they showed antecedents of asthma, left ventricular or renal insufficiency, acute episodes of decompensation, or hematologic pathology. No patient was taking almitrine, theophylline, or angiotensin.

None of the CS practiced endurance training although they had active life styles, participating 2.8 ± 0.4 hr.wk^{-1} in low-intensity recreational activities, essentially gymnastics and hiking. Three of them were former smokers who had stopped smoking 20 years (10 pack.yr^{-1}), 15 years (20 pack.yr^{-1}), and 12 years (15 pack.yr^{-1}) before the study. None of the subjects reported respiratory or cardiac disease, hypertension, or was known to be suffering from any chronic disease. None of the subjects was on any regular medication.

The MA were cyclists training 8±1.9 hr.wk^{-1}, i.e. cycling 10,000± 600 km.y^{-1} (range 6,500-12,000). The MA had been training regularly for 33 ± 6 yr (range 15-60) and five of them had competed at a regional level. Only two MA had ever smoked; one quitted 15 years (24 pack.yr^{-1}), the other 30 years before the study (12 pack.yr^{-1}).

Before admittance to the study, MA and CS were evaluated for their cardiorespiratory health. Subjects having abnormal spirometric data, 12-lead ECG tracing abnormalities, or a supine blood pressure greater than 160/100 mmHg were not allowed to take part to the study. A preliminary maximal exercise test on cycle ergometer was then performed in order to look for any exercise ECG ST-segment depression or significant arrhythmias that would have impeded the subject to take part to the study.

All subjects gave written consent to participate to the study after the design and risks of the study had been described to them.

Experimental protocol

Each subject performed a maximal graded exercise on a cycle ergometer. The exercise test was performed in the laboratory at an ambient temperature of approximately 22°C on a calibrated cycle ergometer (Monark Ergometer 818, Vagberg, Sweden). The test began with a warm-up of 3 min at 20W for COPD and 30W for CS and MA. Pedalling rate remained constant (~60 rpm) throughout the test; the load was increased by increments of 10 W every minute for COPD patients and by 20 to 30 W in CS and MA to reach exhaustion within 8-12 min of exercise. The test was followed by 5 min of passive recovery seated on the cycle ergometer.

Variables	COPD	CS	MA
Age (years)	58±2.4 *	66±1.6	64±1.6
Height (cm)	70±0.9	170±1.3	169±1.7
Body mass (kg)	86±2.8 **	72±2.3	70±1.7 •••
BSA (m^2)	1.94±0.02**	1.81±0.02	1.77±0.02 •••
Max. work rate (watts)	85±5.7 ****	186±6.5 ¤¤¤¤	250±11.2 ••••
$\dot{V}O_{2max}$ (ml.kg^{-1}.min^{-1})	18±1.0 ****	29±1.3 ¤¤¤	41±2.9 ••••
FEV_1 (l)	1.71±0.21****	2.86±0.15	2.77±0.14 ••••
$\%FEV_1$	53.1±2.1****	93.8±6.5	97.8±3.2 ••••

Table 1: Physical characteristics and others variables recorded for the three groups of patients with obstructive pulmonary disease (COPD), control subjects (CS) and endurance-trained master athletes (MA) before and during incremental maximal exercise.

Values are means± SE for 18 COPD, 12 CS and 12 MA. $\dot{V}O_{2max}$, maximal oxygen uptake (ml.kg^{-1}.min^{-1}); BSA, body surface area; FEV_1, forced expiratory volume in 1 s; $\%FEV_1$, %predicted. ¤ CS significantly different from MA (¤ P<0.05, ¤¤ P<0.01, ¤¤¤ P<0.001, ¤¤¤¤ P≤0.0001); * CS significantly different from COPD (* P<0.05, ** P<0.01, *** P<0.001, **** P≤0.0001); • MA significantly different from COPD (• P<0.05, •• P<0.01,••• P<0.001, •••• P≤0.0001. Means without any symbol do not differ significantly.

Ventilatory variables and gas exchanges were measured continuously during the pre-exercise (rest), exercise and recovery periods of the test, using a breath-by-breath automated exercise metabolic system (CPX Medical Graphics, MN, USA). The subjects breathed via a low-resistance breathing valve (2700 Hans-Rudolph, Inc., KS, USA) with a dead space of 100 ml. Expiratory airflow was measured with a pneumotachograph (Type 3, 3800, Hans-Rudolph, Inc., KS, USA) connected to a pressure transducer (DP 250-14, Validyne Engineering Corp., CA, USA). Expiratory gases were analyzed for O_2 with a zirconia solid electrolyte O_2 analyzer and for CO_2 with an infrared analyzer. Before each test, the volume was calibrated by five inspiratory strokes with a 3-liter pump; the gas analyzer was calibrated with two mixtures of gases of known oxygen and carbon dioxide

concentrations (gas mixture: 12% O_2 and 5% CO_2). The subjects were continuously monitored for gas exchange (V_{O_2}, V_{CO_2}, V_E). The exercise metabolic system was coupled with an ECG (Quinton Q 3000, Seattle, WA, USA) and the heart rate (*HR*) data points were averaged on the last 20 sec of each minute. To ensure that $V_{O_{2max}}$ was attained, the following criteria had to be met: 1) a plateau of O_2 uptake despite an increase in work rate, 2) attainment of predicted maximal heart rate (210-0.65.age±10%), 3) respiratory exchange ratio>1.1. When one of these criteria was not met, the mean V_{O_2} measured during the last 20 seconds of exercise testing was reported as symptom-limited V_{O_2}. All variables were monitored 5 minutes before, during maximal exercise, and the 5 minutes of recovery. All the subjects reached the criteria for $V_{O_{2max}}$.

Curve Fitting For the Recovery Response Analysis

The gas exchange and heart rate data were collected during the recovery phase following maximal exercise and each individual evolution curve was fitted to a one-component exponential model [15,3],

$$f(t) = Ae^{-kt} + C \quad (1)$$

where $f(t)$ represents the value of V_{O_2}, V_{CO_2}, V_E or heart rate at t min after exercise, C represents the asymptotic baseline value to which the function returns, and A represents the value in excess of the baseline at the beginning of the recovery phase, *i.e.* $A+C= V_{O_2}$, V_{CO_2}, V_E or heart rate at peak exercise and k is the rate constant of the one-component model.

The gas exchange and heart rate recovery curves from muscular exercise can also be described as the sum of two exponential terms consisting of rapidly decreasing (*kr*) and slowly decreasing (*ks*) components, expressed by an equation:

$$f(t) = A_1 e^{-krt} + A_2 e^{-kst} + C \quad (2)$$

The half time ($T_{1/2exp}$) of V_{O_2}, V_{CO_2}, V_E and *HR* recovery is mathematically defined as 0.693/k, which we calculated from the one-component model. These models were fitted to the 60-s averages of breath-by-breath data. Because the two-component model may not be applied in all patients with COPD, we reported only the results obtained by means of the one-component model.

We also characterized recovery kinetics by simply measuring the half time of recovery ($T_{1/2}$), i.e., the time required for a 50% fall in the peak value of V_{O_2}, V_{CO_2}, V_E and *HR* rate [12] in order to assess its agreement with the half time determined by means of the exponential model ($T_{1/2exp}$) [12]. This method has the advantage of being independent of the chosen models.

Statistics

All results are expressed as means ±SEM. One-way analysis of variance (ANOVA) for repeated measures was used to detect the eventual statistical differences between the COPD, CS and MA groups. For the V_{O_2}, V_{CO_2}, V_E and *HR* kinetics of the individual parameters of the one-component exponential model were fitted by means of an iterative nonlinear technique, using the SigmaPlot graphics package (Jandel Scientific, Erkrath, Germany) for selecting values of C, A, and k by multiple iterations so as to achieve a minimum residual sum of squares. The percentage of variance explained by the use of mono-exponential curve fit was determined by correlation of the observed and predicted values of gas exchange variables and heart rate for each time point and squaring of the Pearson product correlation coefficient. An independent Student's t test or rank sum test (when normality or variance failed) was used for the determination of the significance of inter-group differences and for the statistical comparisons for fitted parameters, resting values and peak exercise test values. To compare the resting and end-recovery values, a paired t test was used.

The Pearson product was used to assess the correlation between the rate constants of the different variables and the relation between the maximal power output (W_{max}) and the rate constants of the recovery variable decays. To compare the half time determined by means of the one-component model and by simple measurement, we used the method of Bland and Altman [16]. The limit for statistical significance was set at $P<0.05$.

RESULTS

Table 1 shows that there were significant inter-group differences in $V_{O_{2max}}$ per kg body weight ($P\leq0.001$) and maximal work rate ($P\leq0.001$). V_{O_2}, V_{CO_2}, V_E and *HR* values before, at the end and following 5 min of maximal exercise are represented in Figure 1 (A, B, C, D).

**Before exercise (Rest):* V_{CO_2} was higher in COPD than both CS ($P<0.05$) and MA ($P<0.01$). *HR* values were lower in MA than in both CS ($P<0.05$) and COPD ($P<0.01$).

**At maximal exercise:* V_{O_2}, V_{CO_2}, V_E *and HR* values were significantly lower in COPD than in MA and CS (Fig. 1). In addition, V_{O_2} was lower in CS than in MA ($P<0.01$).

**End-recovery:* V_{O_2}, V_{CO_2} and V_E values were lower in COPD than CS ($P<0.05$, $P<0.01$, $P<0.01$, respectively), V_{CO_2} ($P<0.05$) and V_E ($P<0.01$) were higher in CS than in MA. *HR* values were lower in MA than in both CS ($P<0.001$) and COPD ($P<0.05$).

* V_{O_2}, V_{CO_2}, V_E *and HR recovery kinetics and half times* (Table 2). The rate constants were determined by fitting the recovery data from each subject to a single exponential equation. The mathematical curve fits accounted for 38-98 % in the residual sum of the squares for recovery variable responses. The V_{O_2} and V_{CO_2} rate constants were significantly higher and the half times ($T_{1/2exp}$) were lower in MA than in CS ($P\leq0.05$) and COPD ($P<0.0001$) and in CS than in COPD ($P\leq0.001$). CS showed a higher rate constant of V_E recovery than COPD ($P<0.0001$), but the difference was not significant compared to MA. On the other hand, CS showed a lower rate constant of *HR* recovery than MA ($P<0.05$), but similar to that of COPD. In addition, the recovery rate constants and the half times ($T_{1/2exp}$) were higher for V_E and lower for *HR* in MA compared to COPD (V_E: $P<0.0001$; *HR*: $P<0.05$).

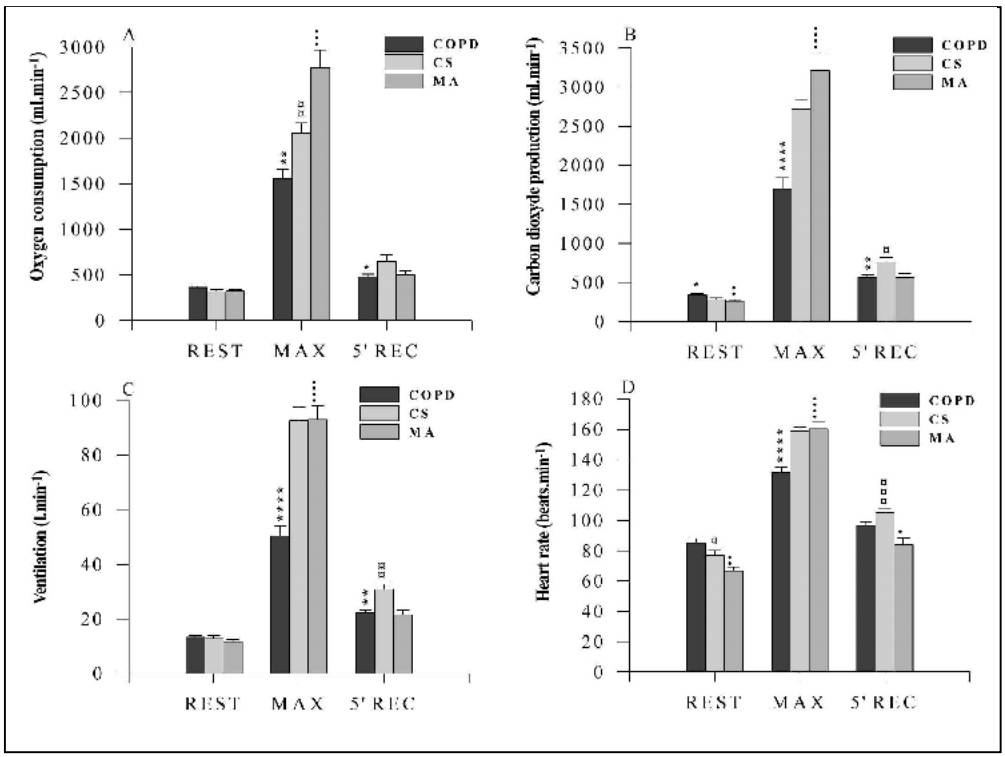

Figure 1 :
Mean Group $\dot{V}O_2$ (Fig.1A, oxygen uptake), $\dot{V}CO_2$ (Fig.1B, Carbon dioxide production), $\dot{V}_E$ (Fig. 1C, ventilation) and *HR* (Fig. 1D, heart rate) responses before exercise (REST), at the end (MAX) and after 5 min recovery (5' REC) from maximal exercise. * CS significantly different from COPD (* P<0.05, ** P<0.01, *** P<0.001, **** P<0.0001); ¤ CS significantly different from MA (¤ P<0.05, ¤¤ P<0.01, ¤¤¤ P<0.001, ¤¤¤¤ P≤0.0001); • MA significantly different from COPD (• P<0.05, •• P<0.01, ••• P<0.001, •••• P<0.0001). Means without any symbol do not differ significantly. See Methods for details.

	A	K	C	$T_{1/2exp}$
	$\dot{V}O_2$			
COPD	1369±94	0.35±0.02 ****	277±44**	2.06±0.12****
CS	1511±71 ¤¤¤¤	0.60±0.05 ¤	543±88	1.25±0.12 ¤
MA	2340±146••••	0.85±0.07••••	441±56•	0.91±0.11••••
	$\dot{V}CO_2$			
COPD	1573±139 ****	0.29±0.01***	239±47 **	2.43±0.11***
CS	2236±105 ¤	0.42±0.03 ¤¤	570±97	1.74±0.12 ¤¤
MA	2882±212 ••••	0.59±0.04••••	342±66	1.25±0.10••••
	$\dot{V}_E$			
COPD	41±35***	0.25±0.02****	9.1±1.7****	3.0±0.25****
CS	67±5.5 ¤	0.51±0.04	24.7±2.4 ¤¤	1.42±0.09
MA	82±3.9••••	0.51±0.06••••	11.9±2.6	1.5±0.17••••
	HR			
COPD	47±3.0**	0.36±0.04	86±2.6	2.49±0.30
CS	66±4.8¤¤	0.37±0.05 ¤	93±3.9 ¤¤	2.13±0.23 ¤
MA	84±3.0 ••••	0.54±0.06 •	74±3.7 •	1.44±0.13 •

Table 2:
Characteristics of the mono-exponential model describing the recovery responses for patients with obstructive pulmonary diseases (COPD), control subjects (CS) and endurance-trained master athletes (MA).
Values are mean ± SE. Units for rate constants (k) are min^{-1}. A et C, parameters of one-component fitted to individual curve (refer to the definition of equation 1) and half time ($T_{1/2exp}$:min) of gas exchange and heart rate during the 5 min of recovery in COPD, CS and MA subjects. ¤ CS significantly different from MA (¤ P<0.05, ¤¤ P<0.01, ¤¤¤ P<0.001, ¤¤¤¤ P≤0.0001); * CS significantly different from COPD (* P<0.05, ** P<0.01, *** P<0.001, **** P≤0.0001); • MA significantly different from COPD (• P<0.05, •• P<0.01, ••• P<0.001,•••• P≤0.0001. Means without any symbol do not differ significantly.

* *Correlation between the $\dot{V}O_2$, $\dot{V}CO_2$, $\dot{V}_E$ and HR rate constants of recovery* (Table 3). There was a close relationship between the $\dot{V}O_2$ and $\dot{V}CO_2$ recovery decays in all groups (P≤0.001), and between $\dot{V}_E$ and both $\dot{V}CO_2$ and $\dot{V}O_2$ but only in COPD and MA ($\dot{V}_E/\dot{V}CO_2$: P≤0.00001, P<0.001, respectively; $\dot{V}_E/\dot{V}O_2$: P<0.01; P<0.01, respectively). However, *HR* recovery decay appeared to be independent of all variables in all groups (data not reported).

**Correlation between the maximal power output (Wmax) and the $\dot{V}O_2$, $\dot{V}CO_2$, $\dot{V}_E$ and HR rate constants of recovery.* In all groups, the kinetics of all variables were unaffected by the power output reached at the end of maximal exercise. Moreover, neither the rate constant nor the half-time of $\dot{V}O_2$ recovery was significantly correlated with peak $\dot{V}O_2$ ($ml.kg^{-1}.min^{-1}$).

The analysis using the Bland and Altman method for assessing agreement between the half time determined by simple measurement ($T_{1/2}$) and the mathematical method ($T_{1/2exp}$) is shown in Figure 2 (2A: $\dot{V}O_2$, 2B: $\dot{V}CO_2$, 2C: $\dot{V}_E$) for COPD and in Figure 3 (3A: $\dot{V}O_2$, 3B: $\dot{V}CO_2$, 3C: $\dot{V}_E$) for MA. The analysis showed that the results of the two methods did agree for $\dot{V}O_2$ (Fig. 2A, 3A) and $\dot{V}CO_2$ (Fig. 2B, 3B) but showed less agreement for $\dot{V}_E$ recovery (2C, 3C) in COPD, although the half time assessed by simple measurement was generally overestimated. Unfortunately, the analysis was not possible for *HR*, because $T_{1/2}$ often exceeded the 5 minutes of recovery in COPD.

	$\dot{V}O_2/\dot{V}CO_2$	$\dot{V}CO_2/V_E$	$\dot{V}O_2/V_E$	$\dot{V}O_2/HR$
Patients (COPD)	0.80 *(P<0.0001)*	0.85 *(P<0.00001)*	0.63 *(P<0.01)*	-0.04 *(P=0.86)*
Control subjects (CS)	0.73 *(P<0.01)*	0.51 *(P=0.08)*	0.50 *(P=0.09)*	0.52 *(P=0.52)*
Master athletes (MA)	0.88 *(P<0.0001)*	0.86 *(P<0.001)*	0.74 *(P<0.01)*	0.35 *(P=0.26)*

Table 3: The relationship between the components of recovery decay (k) of $\dot{V}O_2$, $\dot{V}CO_2$, V_E and HR over the 5 min of recovery.
The data design the values of correlation coefficients (r) between the components of decay of the concerned variables. $\dot{V}O_2$: Oxygen consumption, $\dot{V}CO_2$: dioxide carbon production, V_E: ventilation, and HR: heart rate. Values are statistically significant when P<0.05.

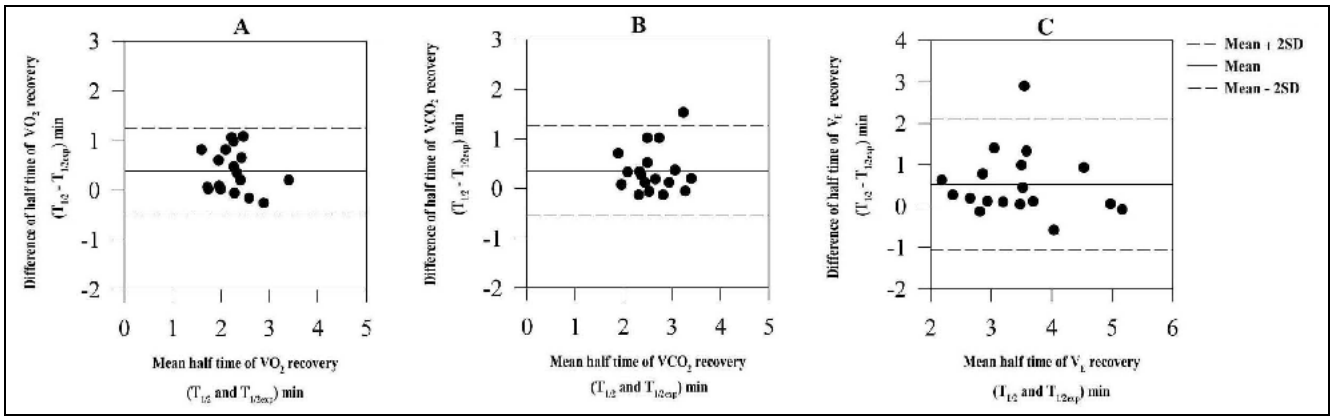

Figure 2: Graphs showing results of Bland and Altman test in COPD. The difference against means of half time assessed by simple measurement ($T_{1/2}$) and mathematically ($T_{1/2exp}$). Fig. 2A ($\dot{V}O_2$), Fig. 2B ($\dot{V}CO_2$), Fig. 2C (V_E), with horizontal lines corresponding to the mean half time ($T_{1/2}$ and $T_{1/2exp}$) and the 2 SD of the differences between the half time measured by the mean of the two methods above and below the mean. The half time is expressed in min.

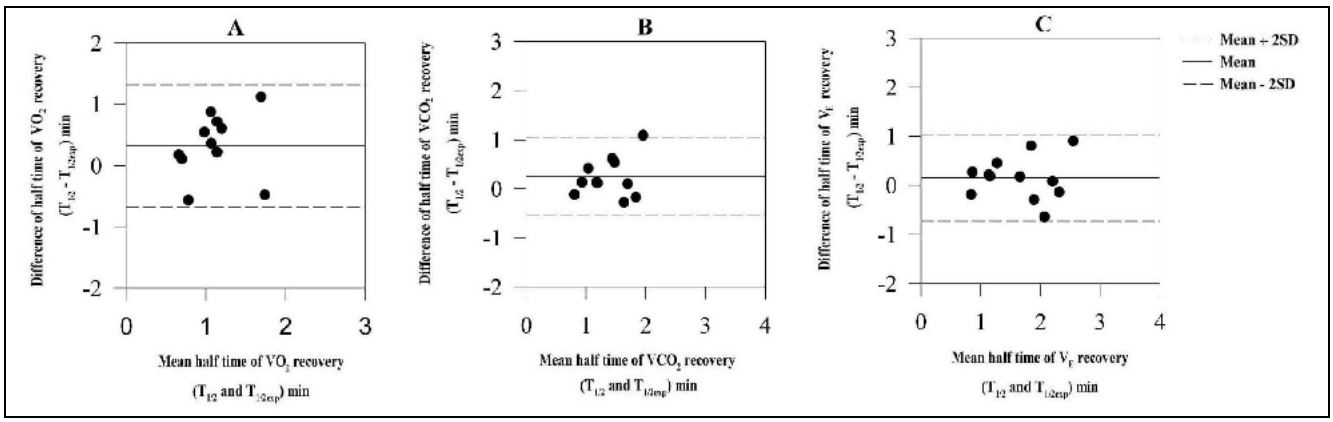

Figure 3: Graphs showing results of Bland and Altman test in MA. The difference against means of half time assessed by simple measurement ($T_{1/2}$) and mathematically ($T_{1/2exp}$). Fig. 3A ($\dot{V}O_2$), Fig. 3B ($\dot{V}CO_2$), Fig. 3C (V_E), with horizontal lines corresponding to the mean half time ($T_{1/2}$ and $T_{1/2exp}$) and the 2 SD of the differences between the half time measured by the mean of the two methods above and below the mean. The half time is expressed in min.

DISCUSSION

The main findings of this study were that during recovery of a maximal graded exercise; the status of respiratory disease impaired the recovery kinetics of $\dot{V}O_2$, $\dot{V}CO_2$ and V_E, whereas the HR recovery was unaltered compared to the control group. In contrast, endurance training status improved the recovery component of $\dot{V}O_2$, $\dot{V}CO_2$ and HR, while V_E appeared to be unaffected. In addition, we showed that the half time ($T_{1/2}$) of $\dot{V}O_2$ recovery may be used as an alternative approach based on simple calculation to assess recovery ability in COPD as well as in normal subjects.

The recovery responses can be assessed by a single or a double exponential equation [12,9,2]. Work intensity and recovery duration may account for the difference in recovery kinetics [17]. However, in the present study, we found that the recovery gas exchange and heart rate kinetics of all three groups were better fitted by a one component exponential model.

We showed that the COPD status affected the rate constants of $\dot{V}O_2$ recovery, as attested by lower values compared to control ones. These data have never been reported. Indeed, these findings indicate that in COPD the

$\dot{V}O_2$ recovered slowly which is confirmed by higher values of its recovery half time ($T_{1/2exp}$). The mechanism of impairment of $\dot{V}O_2$ recovery in COPD could be attributed to skeletal muscle abnormalities. Indeed, in COPD patients, a decrease in oxidative capacity (CS: citrate synthase, SDH) versus glycolitic metabolism (LDH, PFK) has been reported and is well illustrated by a reduced CS/PFK ratio [18]. It has been reported that these patients have a marked decrease in ATP and CPr muscle concentrations [5] compared with control subjects.

We also observed that the $\dot{V}O_2$ recovered faster in older endurance-trained athletes with respect to controls. This latter finding, to our knowledge, had never been reported, but is nevertheless consistent with the observations of Hagberg *et al*. [17], who reported a faster recovery from a constant workload in young subjects after endurance training. The improvement of the MA recovery ability could be related to their training status. It is well known that endurance training reverses the age-related decrease in muscle metabolism in healthy older humans [19]. It has been reported that the master athletes exhibited a number of adaptations to endurance training that distinguished them from the untrained age-matched subjects, including higher citrate synthase [6] and succinate dehydrogenase activities [20]. The fast component of the post-exercise $\dot{V}O_2$ and much of the slow component may be partly explained by the changes in PCr concentration after exercise cessation [4]. PCr_{rate}, which has been shown to be proportional to oxygen consumption in elderly endurance-trained subjects, was significantly correlated with citrate synthase activity in the study of Coggan *et al.* [6]. Moreover, it has been demonstrated, although in young subjects, that endurance training increased the PCr resynthesis [21].

Our study showed no relation between exercise intensity and the kinetics of $\dot{V}O_2$ recovery. Taking into account the relationship between the $\dot{V}O_2$ and PCr, our results could be explained by study of McCully *et al*. [22], who stated that the half-time of PCr resynthesis is independent of the workload attained at peak exercise. Our study focused on the relationship between peak $\dot{V}O_2$ and the half-time of $\dot{V}O_2$ recovery previously reported by Cohen-Solal *et al*. [12]. Nevertheless, our results were in agreement with those of Cohen-Solal *et al.* [12], which reported that the rate of $\dot{V}O_2$ recovery was independent of graded exercise level.

We demonstrated that the recovery kinetics of $\dot{V}CO_2$ and $\dot{V}O_2$ were significantly related in all groups. In contrast, $\dot{V}_E$ was related to $\dot{V}O_2$ and $\dot{V}CO_2$ only in COPD and MA. There are no data in the literature about the relationship between these variables during recovery, but it has been shown that during exercise the $\dot{V}_E$ in normal subjects is more closely related to $\dot{V}CO_2$ than $\dot{V}O_2$ [23]. We showed that the $\dot{V}CO_2$ recovery in MA was faster than in CS. Our findings could be explained by a slowing down of CO_2 elimination from blood because Préfaut *et al*. [10] observed a higher level of $PaCO_2$ during recovery in MA compared to controls. The difference in substrate utilization patterns is another possible explanation. Endurance training shifts basal substrate utilization toward greater fat oxidation in elderly individuals [24]. The high ~P: CO_2 ratio for fatty acids results in a relative CO_2 production rate that is 30% less than for carbohydrate utilization [25].

Préfaut *et al*. [10] also demonstrated a hypoventilation in these highly trained elderly athletes during graded exercise, whereas we found that $\dot{V}_E$ recovery in MA and CS was similar. This result may be partly explained by the similarity in values of $\dot{V}_E$ at peak exercise. In addition, the range of accuracy of the mathematical model and/or the significantly higher work rate reached by MA must be taken into account, as they may contribute to reduce the differences in ventilatory responses. However, the factors responsible for $\dot{V}_E$ recovery cannot be established from the present data or from current literature and require further study.

COPD patients exhibited a slower $\dot{V}CO_2$ recovery compared to controls. Our results agree with the observations of Chick *et al*. [9], which attributed the slower $\dot{V}CO_2$ recovery in COPD to the mechanical limitation in attainment of adequate alveolar ventilation to rapidly reduce CO_2 body stores to resting levels. This may also be explained by the findings of Jakobsson *et al*. [18], who reported evidence of augmented glycolysis in COPD compared with healthy subjects, and those of Brooks [26], who found that chronic hypoxia increases a glucose dependency. Our results of increased resting $\dot{V}CO_2$ and reduced performance support these latter findings.

Compared to control subjects, MA showed a faster exponential decline in *HR*, whereas COPD exhibited a similar *HR* recovery decay. There are no data in the literature about trained subjects to which our one-component values of *HR* recovery in MA may be compared. However, the half-time values ($T_{1/2exp}$) in MA are the same as in previous studies for COPD [9,3]. Moreover, Darr *et al*. [11] obtained by means of another mathematical method the same results in MA, i.e. a faster *HR* decay. The mechanisms that contribute to *HR* decline in the post-exercise period are not clearly defined. Nevertheless, the faster heart rate recovery in MA could be explained by the training influences on post-exercise *HR* via 1) alterations in neural and intrinsic control as suggested by Darr *et al.* [11], 2) an increase in both vagal and sympathetic modulation [27] and 3) the increase in left ventricular mass index observed in older endurance runners [28].

The similar *HR* kinetics found in COPD and CS conflicts with a previous report [9]. Nevertheless, Cohen-Solal *et al*. [12] showed in cardiac patients that in spite of the disease status, the kinetics of *HR* recovery in patients are similar to that of controls. The similar responses in our study could be explained by the lower physical fitness of the trained patients, which had a limiting effect on *HR* recovery responses. Our data, which showed that *HR* was unrelated to exercise intensity, conflicts with previous findings suggesting that the exercise intensity affects the *HR* recovery pattern [29]. This discrepancy in findings may be due to the effect of age and/or to a difference in testing protocol, i.e. work rate: incremental rate vs. constant work rate. On the other hand, our results showed that the *HR* kinetics were independent of all the gas exchange variables, suggesting that the mechanisms of regulation were

independent.

Lastly, our study demonstrated that the $\dot{V}O_2$ half time ($T_{1/2}$) assessed by a simple measurement may constitute an appropriate method in clinical routine to assess the recovery ability in COPD and MA. The Bland and Altman analysis showed that the $T_{1/2}$ of $\dot{V}_E$ was less accurate than the $T_{1/2}$ of $\dot{V}O_2$ and $\dot{V}CO_2$, particularly in MA. This may be due to the difference in the recovery kinetics of gas exchanges, which have a trend toward a biexponential curve in most MA, in contrast to COPD, who exhibited a monoexponential evolution. The Bland and Altman analysis cannot be applied for HR because $T_{1/2}$ was often beyond the 5-min recovery, particularly in COPD. Further research is therefore needed over a much longer *HR* recovery time to see whether the $T_{1/2}$ may also be used for *HR* as an index of recovery capacity.

We conclude that endurance-training status improves the rate of recovery responses in contrast to the status of disease, which delays them. In addition, our results suggest that the profile of gas exchange and heart rate recovery curves could be modified by training and disease status. Our results further suggest that the half time ($T_{1/2}$) of $\dot{V}O_2$ recovery may be used to assess the recovery capacity in healthy subjects and COPD patients.

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