

Clinical Study

Early-Phase Recovery of Cardiorespiratory Measurements after Maximal Cardiopulmonary Exercise Testing in Patients with Chronic Obstructive Pulmonary Disease

Marie Bellefleur,¹ David Debeaumont,² Alain Boutry,² Marie Netchitailo,²
Antoine Cuvelier,¹ Jean-François Muir,¹ Catherine Tardif,^{2,3} and Jérémy Coquart⁴

¹Service de Pneumologie, Hôpital de Bois-Guillaume, CHU de Rouen, 76031 Rouen Cedex, France

²Service de Physiologie Digestive, Urinaire, Respiratoire et Sportive, CHU de Rouen, 76000 Rouen, France

³UPRES EA 3830, GRHV, 76000 Rouen, France

⁴CETAPS, EA 3832, UFR STAPS, Université de Rouen, 76821 Mont Saint Aignan, France

Correspondence should be addressed to Jérémy Coquart; jeremy.coquart@yahoo.com

Received 28 July 2016; Revised 18 October 2016; Accepted 27 October 2016

Academic Editor: Stefano Centanni

Copyright © 2016 Marie Bellefleur et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Background. This study investigated respiratory gas exchanges and heart rate (HR) kinetics during early-phase recovery after a maximal cardiopulmonary exercise test (CPET) in patients with chronic obstructive pulmonary disease (COPD) grouped according to airflow limitation. **Methods.** Thirty control individuals (control group: CG) and 81 COPD patients (45 with “mild” or “moderate” airflow limitation, COPD_{I-II}, versus 36 with “severe” or “very severe” COPD, COPD_{III-IV}) performed a maximal CPET. The first 3 min of recovery kinetics was investigated for oxygen uptake ($\dot{V}O_2$), minute ventilation (\dot{V}_E), respiratory equivalence, and HR. The time for $\dot{V}O_2$ to reach 25% ($T_{1/4}\dot{V}O_2$) of peak value was also determined and compared. **Results.** The $\dot{V}O_2$, \dot{V}_E , and HR recovery kinetics were significantly slower in both COPD groups than CG ($p < 0.05$). Moreover, COPD_{III-IV} group had significantly higher $\dot{V}O_2$ and \dot{V}_E during recovery than COPD_{I-II} group ($p < 0.05$). $T_{1/4}\dot{V}O_2$ significantly differed between groups ($p < 0.01$; 58 ± 18 s in CG, 79 ± 26 s in COPD_{I-II} group, and 121 ± 34 s in COPD_{III-IV}) and was significantly correlated with forced expiratory volume in one second in COPD patients ($p < 0.001$, $r = 0.53$) and with peak power output ($p < 0.001$, $r = 0.59$). **Conclusion.** The COPD groups showed slower kinetics in the early recovery period than CG, and the kinetics varied with severity of airflow obstruction.

1. Introduction

Patients with chronic obstructive pulmonary disease (COPD) are characterized by dyspnea and physical exercise intolerance, both of which impair the ability to participate in physical activities and lower the quality of life [1–3]. The cardiopulmonary exercise test (CPET) is the standard test to investigate the pathophysiological mechanisms of dyspnea and evaluate physical exercise tolerance [4, 5]. Indeed, exercise intolerance in COPD patients is often demonstrated during CPET by an early ventilatory threshold and/or low peak oxygen uptake ($\dot{V}O_{2\text{peak}}$). However, the cardiorespiratory data measured during the recovery period after CPET may also provide indications of physical fitness.

Oxygen uptake ($\dot{V}O_2$) and heart rate (HR) kinetics during recovery after physical exercise are indicators of physical fitness and cardiovascular health [6]. The recovery period has been widely studied in healthy individuals and patients with cardiac disease [7–9]. For example, the $\dot{V}O_2$ kinetics during recovery after submaximal and maximal exercise is prolonged in heart failure patients and closely correlated with indicators of physical fitness (e.g., $\dot{V}O_{2\text{peak}}$). Thus, authors attempted to find physical fitness indicators from the physiological data collected during the recovery period [7].

The half-time recovery of $\dot{V}O_2$ (i.e., $T_{1/2}\dot{V}O_2$), which is the time required for a 50% fall in the $\dot{V}O_{2\text{peak}}$, was identified as an indicator of physical fitness in patients with cardiac disease [7]. However, few studies have examined $T_{1/2}\dot{V}O_2$

or other potential indicators of physical fitness (such as $T_{1/4}\dot{V}O_2$, which corresponds to quarter-time of recovery in $\dot{V}O_2$) in patients with respiratory diseases, especially COPD [10].

The aim of the current study was to examine the respiratory gas exchanges (specifically for $\dot{V}O_2$) and HR kinetics during the early recovery phase after a maximal CPET according to COPD severity. We hypothesized that $\dot{V}O_2$ and HR kinetics would be significantly slower in patients with severe COPD.

2. Materials and Methods

2.1. Population. In this retrospective, observational, routine clinical practice study, all control individuals and COPD patients (men and women) who had performed a CPET on a cycle ergometer between January 1st 2012 and December 31st 2015 at the Rouen University Hospital, France, were included. All procedures performed in this study were in accordance with the ethical standards of the institutional and national research committee and with the 1964 Helsinki declaration and its later amendments.

Thirty control individuals (*i.e.*, control group: CG) and 81 COPD patients participated in the study (Table 1). The COPD patients were assigned to one of two groups depending on the severity of airflow limitation (*i.e.*, COPD_{I-II}, 45 patients with “mild” or “moderate” airflow limitation, versus COPD_{III-IV}, 36 patients with “severe” or “very severe” COPD; Table 1).

Exclusion criteria were respiratory diseases other than COPD, recent exacerbation (in the 6 months preceding inclusion), chronic heart failure (left ventricular ejection fraction < 55%), undernutrition (body mass index: BMI < 18.5 kg·m⁻²), severe obesity (BMI ≥ 35 kg·m⁻²), and any muscular or metabolic disease. Medications that could influence heart rate and arterial tension are presented in Table 2. Moreover, when the physician decided to stop the CPET because of myocardial ischemia, arrhythmia, or systemic hypertension, the participant was excluded. Last, none of the control individuals or patients was engaged in an exercise training program prior to the study, and none of the participants was considered as very deconditioned (*i.e.*, ventilatory threshold < 40% $\dot{V}O_{2peak}$).

2.2. Protocol. Before CPET, anthropometric (*i.e.*, height and BMI) and spirometric (*i.e.*, forced expiratory volume in one second (FEV₁) and forced vital capacity (FVC)) data were collected for each participant. The percentage of the vital capacity expiring in the first second of maximal expiration (*i.e.*, FEV₁/FVC × 100) was calculated in order to confirm COPD (FEV₁/FVC × 100 < 70%). The severity of airflow limitation was determined from FEV₁, according to the Global Initiative for Chronic Obstructive Lung Disease [11]. When FEV₁/FVC × 100 ≥ 70%, the patient was included in the control group.

Then, participants performed a symptom-limited CPET on an electromagnetically braked cycle ergometer (BV Lode®, Groningen, Netherlands) in accordance with Palange et al. [12]. Following a 3-minute warm-up, power output gradually

increased every minute with increments of 5 to 20 W according to the patient’s fitness level and severity of airflow obstruction until the point of maximal effort (*i.e.*, the participant failed to maintain a pedaling rate above 60 rpm for more than 5 s, unless the test was terminated for medical reasons). The initial and subsequent increments in power output were set to ensure exercise duration between 8 and 12 min. A pedaling rate of 60–70 rpm was maintained throughout CPET. The patients were instructed to attain the highest possible power output. After the point of maximal effort, a 3-minute recovery period was investigated. Expired air (*i.e.*, $\dot{V}O_2$, carbon dioxide output: $\dot{V}CO_2$, and minute ventilation: \dot{V}_E) was continuously recorded via a breath-by-breath system (Medisoft®, Sorinnes, Belgium), calibrated in accordance with the manufacturer’s guidelines (before each CPET) and averaged every 1 min (over 30 s). HR was also recorded with a 12-lead electrocardiogram (Medcard, Medisoft®, Sorinnes, Belgium).

Maximal effort was checked according to the following criteria: (1) respiratory exchange ratio ≥ 1.1, (2) ventilatory reserve ≤ 30%, (3) peak HR ≥ 90% of the theoretical peak HR (*i.e.*, 210 – 0.65 × age), and (4) subjective state of extreme physical tiredness. In all cases, at least three of the four criteria were met, or the participant was excluded. When maximal effort was confirmed, actual $\dot{V}O_{2peak}$ was considered as the highest $\dot{V}O_2$ over 30 s. At this point, respiratory gas exchanges and HR were collected.

During the recovery period, $\dot{V}O_2$, $\dot{V}CO_2$, \dot{V}_E , and HR were measured for 3 min and averaged every 1 min (over 30 s). Oxygen equivalence ($EqO_2 = \dot{V}_E/\dot{V}O_2$) and carbon dioxide equivalence ($EqCO_2 = \dot{V}_E/\dot{V}CO_2$) were computed, and the time needed for $\dot{V}O_2$ to reach 25% of its peak value was recorded ($T_{1/4}\dot{V}O_2$).

2.3. Statistical Analysis. Data are reported as means and standard deviation. For all data, normal Gaussian distributions were verified by the Shapiro-Wilk test and homogeneity of variance by the Levene test. When the data did not pass the test for normality and/or homogeneity of variance, they were log transformed.

For anthropometric and spirometric data, a general linear model with a 1-way design was used to test the group effect (*i.e.*, CG versus COPD_{I-II} versus COPD_{III-IV}). If significant differences were obtained, a Bonferroni *post hoc* test was conducted.

Possible differences in the recovery period were tested using the general linear model (groups) for repeated measures (*i.e.*, recovery period: 0, 60, 120, and 180 s). The sphericity was checked by the Mauchly test and, when it was not met, the significance of *F*-ratios was adjusted according to the Greenhouse-Geisser procedure or the Huynh-Feldt procedure. When significant differences were obtained, a Bonferroni *post hoc* test was conducted.

For $T_{1/4}\dot{V}O_2$, a general linear model with a 1-way design was used to examine the group effect (*i.e.*, CG versus COPD_{I-II} versus COPD_{III-IV}). If significant differences were obtained, a Bonferroni *post hoc* test was conducted.

The Pearson product moment correlation was used to evaluate the association between $T_{1/4}\dot{V}O_2$ and peak power output and FEV₁ in COPD groups.

TABLE 1: Mean \pm standard deviation of anthropometric and spirometric data and physiological data measured at voluntary exhaustion according to groups.

Variables	Control group (<i>n</i> = 30)	GOLD _{I-II} group (<i>n</i> = 45)	GOLD _{III-IV} group (<i>n</i> = 36)	All participants (<i>n</i> = 111)
Age (y)	50.2 \pm 15.0	60.1 \pm 9.0 ^a	60.8 \pm 10.2 ^a	57.6 \pm 12.1
BMI (kg·m ⁻²)	24.9 \pm 4.3	27.7 \pm 5.2 ^b	23.4 \pm 4.1	25.6 \pm 5.0
FEV ₁ (L)	3.242 \pm 0.886 ^b	2.062 \pm 0.616 ^{a,b}	1.094 \pm 0.298 ^a	2.067 \pm 1.036
FEV ₁ (%)	105.6 \pm 12.9 ^b	71.3 \pm 12.3 ^{a,b}	39.2 \pm 8.2 ^a	70.2 \pm 27.9
FVC (L)	4.126 \pm 1.160 ^b	3.526 \pm 0.868 ^{a,b}	2.805 \pm 0.740 ^a	3.454 \pm 1.045
FVC (%)	109.8 \pm 14.6 ^b	96.0 \pm 13.4 ^{a,b}	77.8 \pm 13.1 ^a	93.8 \pm 18.4
FEV ₁ /FVC (%)	78.8 \pm 5.8 ^b	59.2 \pm 8.8 ^{a,b}	41.3 \pm 8.3 ^a	58.7 \pm 16.5
IC/TLC (%)	45.6 \pm 5.9 ^b	38.4 \pm 8.9 ^{a,b}	28.3 \pm 6.3 ^a	35.2 \pm 9.7
DLCO (mmol·kPa ⁻¹ ·min ⁻¹)	6.737 \pm 1.420 ^b	5.351 \pm 2.240 ^{a,b}	3.632 \pm 1.821 ^a	5.035 \pm 2.244
$\dot{V}O_2$ peak (L·min ⁻¹)	2.049 \pm 0.876 ^b	1.410 \pm 0.508 ^{a,b}	0.933 \pm 0.232 ^a	1.428 \pm 0.713
\dot{V}_E peak (L·min ⁻¹)	82.8 \pm 35.2 ^b	66.5 \pm 21.7 ^{a,b}	40.4 \pm 9.9 ^a	62.4 \pm 28.7
HRpeak (bpm)	164 \pm 17	136 \pm 20 ^a	127 \pm 19 ^a	140 \pm 24

COPD: chronic obstructive pulmonary disease; *n*: sample size; BMI: body mass index; FEV₁: forced expiratory volume in 1 second; FVC: forced vital capacity; IC: inspiratory capacity; TLC: total lung capacity; DLCO: diffusing capacity of the lungs for carbon monoxide; $\dot{V}O_2$ peak: peak oxygen uptake; \dot{V}_E peak: peak minute ventilation; HRpeak: peak heart rate. ^aSignificantly different from control group ($p < 0.05$). ^bSignificantly different from COPD_{III-IV} group ($p < 0.05$).

TABLE 2: Medication that could influence heart rate and arterial tension.

Variables	Control group (<i>n</i> = 30)	COPD group (<i>n</i> = 81)
Short-acting β_2 -agonists (<i>n</i>)	0	69
Long-acting β_2 -agonists (<i>n</i>)	0	48
Ipratropium bromide (<i>n</i>)	0	19
Theophylline (<i>n</i>)	1	0
Calcium channel blockers (<i>n</i>)	6	17
Angiotensin converting enzyme inhibitors (<i>n</i>)	3	11
Angiotensin II receptor antagonists (<i>n</i>)	3	10
Leukotriene receptor antagonist (<i>n</i>)	1	3
Diuretics (<i>n</i>)	4	8

COPD: chronic obstructive pulmonary disease; *n*: sample size.

Statistical significance was set at $p < 0.05$ and all analyses were performed with the Statistical Package for the Social Sciences (release 18.0, Chicago, IL, USA).

3. Results

Anthropometric and spirometric data are summarized in Table 1.

Patients in CG were significantly younger than those in the COPD groups ($p < 0.001$, Table 1). BMI was significantly lower in COPD_{III-IV} compared with COPD_{I-II} ($p < 0.001$).

Logically, FEV₁ and FVC (both expressed in L and %) were significantly different between groups ($p < 0.001$, Table 1). Inspiratory capacity/total lung capacity and diffusing capacity of the lungs for carbon monoxide were significantly higher in CG compared with the COPD groups, and these values were significantly lower in COPD_{III-IV} compared with COPD_{I-II} ($p < 0.05$, Table 1).

At maximal effort, $\dot{V}O_2$ peak and peak of \dot{V}_E were significantly higher in CG compared with the COPD groups ($p < 0.001$, Table 1). Moreover, these values were significantly lower in COPD_{III-IV} than COPD_{I-II} ($p < 0.001$). For peak of HR, the only significant difference was noted between CG and the two COPD groups ($p < 0.001$, Table 1).

After peak exercise, all physiological data (*i.e.*, $\dot{V}O_2$, \dot{V}_E , EqO₂, EqCO₂, and HR) were significantly different at each minute of recovery ($p < 0.05$), except HR between the peak exercise and 1st min of recovery ($p = 0.07$) and EqO₂ between the 2nd and 3rd minutes ($p = 0.06$), while nonsignificant trends were noticed. Figure 1 shows that the recovery kinetics of $\dot{V}O_2$, \dot{V}_E , and HR were significantly slower in both COPD groups than CG ($p < 0.05$, Figure 1). Moreover, COPD_{III-IV} group had significantly higher $\dot{V}O_2$ and \dot{V}_E during the recovery in comparison with COPD_{I-II} group ($p < 0.05$).

HR decreased by 12, 7, and 5 bpm each minute during the recovery period, respectively, in CG, COPD_{I-II}, and COPD_{III-IV}. Moreover, HR at the first minute was decreased by 5, 3, and 1 bpm, respectively, in CG, COPD_{I-II}, and COPD_{III-IV}.

Figure 2 shows a bar graph of the mean values of T_{1/4} $\dot{V}O_2$ in the three groups. T_{1/4} $\dot{V}O_2$ was 58 \pm 18 s in CG, 79 \pm 26 s in COPD_{I-II}, and 121 \pm 34 s in COPD_{III-IV}. Significant differences between groups were observed ($p < 0.01$). Moreover, T_{1/4} $\dot{V}O_2$ was significantly correlated with FEV₁ in the

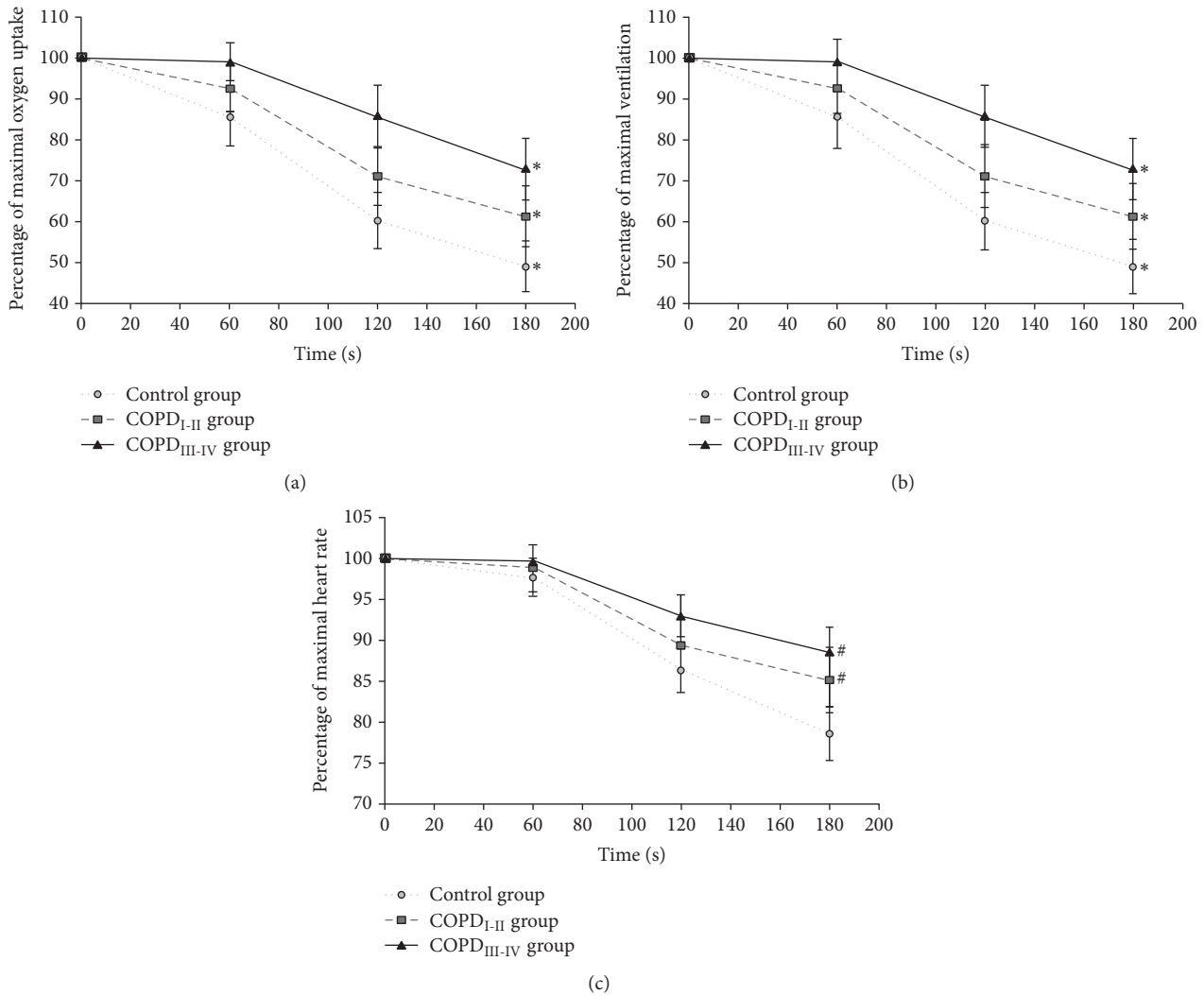


FIGURE 1: Kinetics of recovery of oxygen consumption (a), ventilation (b), and heart rate (c) according to groups. COPD: chronic obstructive pulmonary disease. *Significantly different from both groups ($p < 0.05$). #Significantly different from control group ($p < 0.05$).

COPD patients ($p < 0.001$, $r = 0.53$) and with peak power output ($p < 0.001$, $r = 0.59$).

4. Discussion

The aim of the current study was to examine the $\dot{V}O_2$, \dot{V}_E , E_{qO_2} , E_{qCO_2} , and HR kinetics during the early recovery phase after a maximal CPET, according to the COPD severity. Our main results showed slower recovery kinetics in both COPD groups compared with CG, with significantly longer $T_{1/4}\dot{V}O_2$ in the COPD groups that varied with the severity of airflow obstruction.

After an (acute) aerobic exercise, $\dot{V}O_2$ does not immediately return to the resting value. This “excess postexercise oxygen consumption” (EPOC) [13] has an immediate phase during which oxygen is required to rebuild adenosine triphosphate and phosphocreatine. Then, in the following minutes, EPOC is thought to be implicated in the removal of accumulated lactate acid [13]. The recovery period is thus devoted to the repayment of the oxygen debt generated during physical

exercise. The high EPOC noted in the current study (Figure 1) may be partially due to the muscle dysfunctions common to COPD patients. Indeed, these patients often show a decreased capacity for aerobic energy metabolism manifested by an increased recovery time for phosphocreatine, as previously shown by 31-phosphorous magnetic resonance spectroscopy [14, 15].

Prolonged $\dot{V}O_2$ kinetics during the recovery period have been observed in various situations like deconditioning [16] and COPD [10]. For example, all respiratory gas exchanges were slowed in COPD patients compared with healthy individuals [10]. The present results confirm these findings, with a significantly slower recovery of $\dot{V}O_2$ and \dot{V}_E (Figure 1). The physiological mechanisms underlying the slower kinetics during exercise recovery are not completely understood, but part of the explanation is the slow recovery of energy stores in peripheral skeletal muscles, as proposed by Thompson et al. [17].

The insidious development of airflow limitation and dynamic hyperinflation over many years in COPD patients

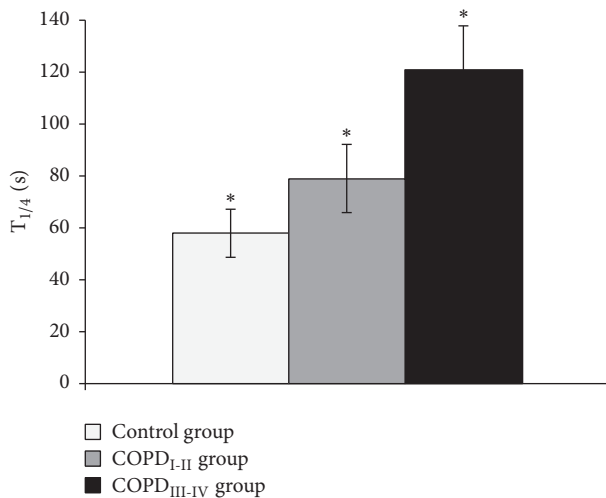


FIGURE 2: Bar graph of the mean values of quarter-time of recovery in oxygen uptake ($T_{1/4}$) according to groups. COPD: chronic obstructive pulmonary disease. *significantly different from both groups ($p < 0.01$).

leads to some structural and mechanical adaptations, which preserve the functional strength of the overburdened inspiratory muscles, particularly the diaphragm [18, 19]. It is thought that the function of intercostal and sternomastoid muscles is at less of a disadvantage compared to the diaphragm in the presence of severe hyperinflation [20]. However, despite this temporal adaptation, the presence of severe hyperinflation means that the ability to increase ventilation when the demand arises is greatly limited in COPD patients [18]. Consequently, this constraint may probably explain the slower recovery of \dot{V}_E reported in our patients with severe COPD.

Cohen-Solal et al. [7] reported that $T_{1/2}\dot{V}O_2$ was an indicator of physical fitness in patients with chronic heart failure. However, $T_{1/2}\dot{V}O_2$ determination requires a long recovery period (often 6 min or more). For example, in the current study, it was not possible to determine $T_{1/2}\dot{V}O_2$ for 9 individuals in CG, 25 patients in COPD_{I-II}, and 25 patients in COPD_{III-IV}. We therefore preferred to use $T_{1/4}\dot{V}O_2$. This indicator is interesting primarily because it is a potential alternative to $T_{1/2}\dot{V}O_2$. Indeed, $T_{1/4}\dot{V}O_2$ was significantly different between groups (*i.e.*, higher in COPD patients) and significantly linked with disease severity (*i.e.*, FEV_1). Therefore, if the validity, reliability, sensitivity, and usefulness of $T_{1/4}\dot{V}O_2$ are confirmed in COPD patients, this indicator might be used as a criterion for therapeutic interventions that decrease operating lung volumes with oxygen supplementation or acute bronchodilator therapy during the recovery period [21–23]. Further studies are nevertheless needed before $T_{1/4}\dot{V}O_2$ can be considered for routine clinical practice.

Continuous aerobic exercise has beneficial effects on patients with severe COPD [24, 25]. However, interval training, which consists of regularly alternating high intensity exercise and low intensity recovery periods, seems to provide better clinical and physiological benefits to patients with moderate and severe COPD, including increased total exercise duration, application of intense loads on peripheral

muscles for sufficiently long periods of time, lower minute ventilation, lower rates of dynamic hyperinflation, and enhanced exercise tolerance and quality of life [26–28]. Therefore, interval training may be better than continuous exercise for COPD patients. The interval training protocols are nevertheless heterogeneous and no consensus exists about the optimal intensity and duration of the two phases (*i.e.*, effort and recovery periods), although these exercise characteristics (*i.e.*, intensity and duration) are major determinants of the physiological adaptations that occur during training programs [29]. The present study suggests that the duration of each phase must be individualized on the basis of the COPD severity, with a longer recovery period for patients with severe COPD. Further studies are required to investigate the appropriate time and/or interval training workload for these patients.

As indicated in the Methods section, the COPD patients were assigned to one of two groups based on the severity of airflow limitation (*i.e.*, COPD_{I-II} versus COPD_{III-IV}). It might have been preferable to classify the patients into four groups to examine the sensitivity of $T_{1/4}\dot{V}O_2$ in greater detail, but our population included only ten patients with mild COPD (*i.e.*, COPD_I) and six patients with very severe COPD (*i.e.*, COPD_{IV}). It thus was not possible to perform statistical analyses on four groups of COPD patients because of the small sample sizes.

Another possible limitation of the current study concerns the selected exhaustion criteria. Indeed, although the maximal effort was confirmed from at least three of the four exhaustion criteria, it is not sure that all participants have achieved their maximal capacity. For example, a ventilatory reserve $\leq 30\%$ was used to check the ventilatory limitation. This threshold (*i.e.*, value $\leq 30\%$) is commonly used in the literature [4, 30, 31], but it remains wide, and it may not be adapted for all individuals. Indeed, recently Mirdamadi et al. [32] have reported a mean ventilatory reserve = 30.9% (which is according to our study), but their study revealed also wide standard deviation ($\pm 25.1\%$). More specifically, their results showed a ventilatory reserve = $43.1 \pm 25.6\%$ in patients with leg fatigue and only a ventilatory reserve = $16.6 \pm 15.4\%$ in patients without leg fatigue [32]. Consequently, it is possible that in the current study we have considered that CPET was maximal from ventilatory reserve $\leq 30\%$ in COPD patients without leg fatigue, while a low ventilatory reserve should have been researched (approximately $\leq 15\%$ in these patients).

Moreover, as recently reminded by Ha et al. [33], numerous authors have found a large variability in the decrease of HR at 1 min following cessation of exercise (decrease of 8–17 beats when the HR recovery is abnormal), though abnormal HR recovery is commonly defined as ≤ 12 –14 [34, 35]. Consequently, the results of the present study are surprising because we noticed only a mean decrease of 5 beats in CG. This result may be explained by the possible submaximal CPET (as explained before) and/or the drugs consumed by the participants. Indeed, numerous individuals (in CG and COPD groups) consumed drugs that could influence HR and arterial tension (Table 2). These drugs have limited HRmax and thus the reduction of HR at the first minute of recovery period. Furthermore, the abnormal delayed decrease of HR

in COPD and control groups may be also explained by important deconditioning in both populations.

5. Conclusion

The current study showed slower kinetics in the early recovery period in both COPD groups compared with CG, according to the severity of airflow obstruction. Moreover, $T_{1/4}\dot{V}O_2$ also increased with the severity of COPD. These results may be explained by the disease and might be taken into account in the prescription of interval training exercises.

Abbreviations

BMI:	Body mass index
CG:	Control group
COPD:	Chronic obstructive pulmonary disease
COPD _{I-II} :	Group with “mild” or “moderate” airflow limitation
COPD _{III-IV} :	Group with “severe” or “very severe” airflow limitation
CPET:	Cardiopulmonary exercise test
EPOC:	Excess postexercise oxygen consumption
EqCO ₂ :	Carbon dioxide equivalence
EqO ₂ :	Oxygen equivalence
FEV ₁ :	Forced expiratory volume in one second
FVC:	Forced vital capacity
HR:	Heart rate
$T_{1/2}\dot{V}O_2$:	Half-time recovery of oxygen uptake
$T_{1/4}\dot{V}O_2$:	Quarter-time recovery of oxygen uptake
\dot{V}_E :	Minute ventilation
$\dot{V}CO_2$:	Carbon dioxide output
$\dot{V}O_2$:	Oxygen uptake
$\dot{V}O_{2peak}$:	Peak oxygen uptake.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this article.

Authors' Contributions

Marie Bellefleur and David Debeaumont have full access to all of the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis. Alain Boutry had contributed to collection of data. Marie Bellefleur, David Debeaumont, Marie Netchitailo, Antoine Cuvelier, Jean-François Muir, Catherine Tardif, and Jérémy Coquart have contributed substantially to the study design, data analysis and interpretation, and the writing of the manuscript.

Acknowledgments

The authors thank Mr. Alexandre Bellefleur for his valuable help in the translation of this article.

References

- [1] M. Amann, M. S. Regan, M. Kobitany et al., “Impact of pulmonary system limitations on locomotor muscle fatigue in patients with COPD,” *American Journal of Physiology—Regulatory Integrative and Comparative Physiology*, vol. 299, no. 1, pp. R314–R324, 2010.

- [2] E. Barreiro and J. Gea, “Respiratory and limb muscle dysfunction in COPD,” *COPD: Journal of Chronic Obstructive Pulmonary Disease*, vol. 12, no. 4, pp. 413–426, 2015.
- [3] J. B. Coquart, J. -M. Grosbois, C. Olivier, F. Bart, I. Castres, and B. Wallaert, “Home-based neuromuscular electrical stimulation improves exercise tolerance and health-related quality of life in patients with chronic obstructive pulmonary disease,” *International Journal of Chronic Obstructive Pulmonary Disease*, vol. 11, pp. 1189–1197, 2016.
- [4] B. Aguilaniu and B. Wallaert, *EFX: De l'Interprétation à la Décision Médicale*, Margaux Orange, Paris, France, 2015.
- [5] J. M. Grosbois, C. Riquier, and B. Chehere, “Six-minute stepper test: a valid clinical exercise tolerance test for COPD patients,” *International Journal of Chronic Obstructive Pulmonary Disease*, vol. 11, pp. 657–663, 2016.
- [6] K. E. Sietsema, J. A. Daly, and K. Wasserman, “Early dynamics of O₂ uptake and heart rate as affected by exercise work rate,” *Journal of Applied Physiology*, vol. 67, no. 6, pp. 2535–2541, 1989.
- [7] A. Cohen-Solal, T. Laperche, D. Morvan, M. Geneves, B. Caviezel, and R. Gourgon, “Prolonged kinetics of recovery of oxygen consumption after maximal graded exercise in patients with chronic heart failure. Analysis with gas exchange measurements and NMR spectroscopy,” *Circulation*, vol. 91, no. 12, pp. 2924–2932, 1995.
- [8] C. R. Cole, E. H. Blackstone, F. J. Pashkow, C. E. Snader, and M. S. Lauer, “Heart-rate recovery immediately after exercise as a predictor of mortality,” *The New England Journal of Medicine*, vol. 341, no. 18, pp. 1351–1357, 1999.
- [9] M. Fortin, P.-Y. Turgeon, É. Nadreau et al., “Prognostic value of oxygen kinetics during recovery from cardiopulmonary exercise testing in patients with chronic heart failure,” *The Canadian Journal of Cardiology*, vol. 31, no. 10, pp. 1259–1265, 2015.
- [10] T. W. Chick, T. G. Cagle, F. A. Vegas, J. K. Poliner, and G. H. Murata, “Recovery of gas exchange variables and heart rate after maximal exercise in COPD,” *Chest*, vol. 97, no. 2, pp. 276–279, 1990.
- [11] GOLD, Global strategy for the diagnosis management, and prevention of chronic obstructive pulmonary disease: updated 2014, <http://www.goldcopd.org/2014>.
- [12] P. Palange, S. A. Ward, K.-H. Carlsen et al., “Recommendations on the use of exercise testing in clinical practice,” *European Respiratory Journal*, vol. 29, no. 1, pp. 185–209, 2007.
- [13] G. A. Gaesser and G. A. Brooks, “Metabolic bases of excess post-exercise oxygen consumption: a review,” *Medicine and Science in Sports and Exercise*, vol. 16, no. 1, pp. 29–43, 1984.
- [14] T. Kutsuzawa, S. Shioya, D. Kurita, M. Haida, Y. Ohta, and H. Yamabayashi, “Muscle energy metabolism and nutritional status in patients with chronic obstructive pulmonary disease. A 31P magnetic resonance study,” *American Journal of Respiratory and Critical Care Medicine*, vol. 152, no. 2, pp. 647–652, 1995.
- [15] B. Wuyam, J. F. Payen, P. Levy et al., “Metabolism and aerobic capacity of skeletal muscle in chronic respiratory failure related to chronic obstructive pulmonary disease,” *European Respiratory Journal*, vol. 5, no. 2, pp. 157–162, 1992.
- [16] V. A. Convertino, D. J. Goldwater, and H. Sandler, “VO₂ kinetics of constant-load exercise following bed-rest-induced deconditioning,” *Journal of Applied Physiology: Respiratory, Environmental and Exercise Physiology*, vol. 57, no. 5, pp. 1545–1550, 1984.

- [17] C. H. Thompson, R. J. O. Davies, G. J. Kemp, D. J. Taylor, G. K. Radda, and B. Rajagopalan, "Skeletal muscle metabolism during exercise and recovery in patients with respiratory failure," *Thorax*, vol. 48, no. 5, pp. 486–490, 1993.
- [18] D. E. O'Donnell and P. Laveneziana, "Physiology and consequences of lung hyperinflation in COPD," *European Respiratory Review*, vol. 15, no. 100, pp. 61–67, 2006.
- [19] T. Similowski, S. Yan, A. P. Gauthier, P. T. Macklem, and F. Bellemare, "Contractile properties of the human diaphragm during chronic hyperinflation," *The New England Journal of Medicine*, vol. 325, no. 13, pp. 917–923, 1991.
- [20] J. T. Sharp, "The respiratory muscles in chronic obstructive pulmonary disease," *The American Review of Respiratory Disease*, vol. 134, no. 5, pp. 1089–1091, 1986.
- [21] N. J. Stevenson and P. M. A. Calverley, "Effect of oxygen on recovery from maximal exercise in patients with chronic obstructive pulmonary disease," *Thorax*, vol. 59, no. 8, pp. 668–672, 2004.
- [22] P. Laveneziana, P. Palange, J. Ora, D. Martolini, and D. E. O'Donnell, "Bronchodilator effect on ventilatory, pulmonary gas exchange, and heart rate kinetics during high-intensity exercise in COPD," *European Journal of Applied Physiology*, vol. 107, no. 6, pp. 633–643, 2009.
- [23] A. Somfay, J. Porszasz, S. M. Lee, and R. Casaburi, "Dose-response effect of oxygen on hyperinflation and exercise endurance in nonhypoxaemic COPD patients," *European Respiratory Journal*, vol. 18, no. 1, pp. 77–84, 2001.
- [24] B. McCarthy, D. Casey, D. Devane, K. Murphy, E. Murphy, and Y. Lacasse, "Pulmonary rehabilitation for chronic obstructive pulmonary disease," *The Cochrane Database of Systematic Reviews*, vol. 2, pp. 1–209, 2015.
- [25] T. L. Griffiths, M. L. Burr, I. A. Campbell et al., "Results at 1 year of outpatient multidisciplinary pulmonary rehabilitation: a randomised controlled trial," *The Lancet*, vol. 355, no. 9201, pp. 362–368, 2000.
- [26] I. Vogiatzis, O. Georgiadou, S. Golemati et al., "Patterns of dynamic hyperinflation during exercise and recovery in patients with severe chronic obstructive pulmonary disease," *Thorax*, vol. 60, no. 9, pp. 723–729, 2005.
- [27] E. A. Kortianou, I. G. Nasis, S. T. Spetsioti, A. M. Daskalakis, and I. Vogiatzis, "Effectiveness of interval exercise training in patients with COPD," *Cardiopulmonary Physical Therapy Journal*, vol. 21, no. 3, pp. 12–19, 2010.
- [28] M. K. Beauchamp, M. Nonoyama, R. S. Goldstein et al., "Interval versus continuous training in individuals with chronic obstructive pulmonary disease—a systematic review," *Thorax*, vol. 65, no. 2, pp. 157–164, 2010.
- [29] R. S. Taylor, V. A. Sagar, E. J. Davies et al., "Exercise-based rehabilitation for heart failure," *The Cochrane Database of Systematic Reviews*, vol. 4, Article ID CD003331, 2014.
- [30] B. Aguilaniu, R. Richard, F. Costes et al., "Méthodologie et pratique de l'exploration fonctionnelle à l'exercice (EFX)," *Revue des Maladies Respiratoires*, vol. 24, no. 3, pp. 111–160, 2007.
- [31] B. Aguilaniu and B. Wallaert, "De l'interprétation de l'exploration fonctionnelle d'exercice (EFX) à la décision médicale," *Revue des Maladies Respiratoires*, vol. 30, no. 6, pp. 498–515, 2013.
- [32] M. Mirdamadi, B. Rahimi, E. Safavi, H. Abtahi, and S. Peiman, "Correlation of cardiopulmonary exercise testing parameters with quality of life in stable COPD patients," *Journal of Thoracic Disease*, vol. 8, no. 8, pp. 2138–2145, 2016.
- [33] D. Ha, M. Fuster, A. L. Ries, P. D. Wagner, and P. J. Mazzone, "Heart rate recovery as a preoperative test of perioperative complication risk," *The Annals of Thoracic Surgery*, vol. 100, no. 5, pp. 1954–1962, 2015.
- [34] E. Gimeno-Santos, D. A. Rodriguez, A. Barberan-Garcia et al., "Endurance exercise training improves heart rate recovery in patients with COPD," *COPD*, vol. 11, no. 2, pp. 190–196, 2014.
- [35] M. Lacasse, F. Maltais, P. Poirier et al., "Post-exercise heart rate recovery and mortality in chronic obstructive pulmonary disease," *Respiratory Medicine*, vol. 99, no. 7, pp. 877–886, 2005.