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1.0 Summary (English)

Artefactual Incidence of $\dot{V}O_2$ Plateau and $\dot{V}O_{2max}$ in Historical Studies: Time to Move on

Purpose

Contemporary understanding of the time course of oxygen uptake suggests that traditional discontinuous tests are of insufficient duration to elicit a fully developed $\dot{V}O_2$ response. However, this remains to be empirically demonstrated. Thus, the aims of the present study were (1) to investigate whether early $\dot{V}O_{2max}$ assessments underestimated actual $\dot{V}O_2$, and (2) to investigate whether the apparent $\dot{V}O_2$ plateau observed in classic studies was an artefact of measuring in a non-steady state.

Summary of Facts and Results

Twelve males (age 28 ± 7 y, 1.78 ± 0.05 m, 80 ± 11 kg) each completed a constant speed discontinuous test. The study design replicated the increasing gradient discontinuous test used by Taylor, et al. [1]. $\dot{V}O_2$ data were averaged during the 1.75-2.75 min ($\dot{V}O_{2.Taylor}$) time point and the final minute of each test ($\dot{V}O_{2.Final}$). A paired samples *t*-test was used to evaluate differences in $\dot{V}O_{2peak.Taylor}$ and $\dot{V}O_{2peak.Final}$

The $\dot{V}O_{2peak.Final}$ was found to be significantly higher than $\dot{V}O_{2peak.Taylor}$ ($P<0.001$, $d = 1.18$). The slope of the $\dot{V}O_2$ response, calculated from the last completed gradient for each participant was significantly different from zero during the 1.75-2.75 min (Taylor: $P=0.009$, $d = 1.58$; Final: $P=0.02$, $d = 0.29$).

Conclusion

$\dot{V}O_2$ plateau in historical studies was artefactual. Further investigation, without the fallacious assumptions of historical studies, may enable exercise physiologists and practitioners to determine which combination of exercise protocol and method of data acquisition is most conducive to elicit and detect a $\dot{V}O_2$ plateau.

Key words: Maximal; Oxygen uptake; Plateau; Discontinuous; Measurement

Le plateau définissant la VO2max dans les études classiques était-il un artefact

Résumé (Français)

Introduction

Les données actuelles sur la cinétique dans le temps de la consommation d'oxygène portent à penser que les tests discontinus traditionnels sont d'une durée insuffisante pour solliciter pleinement la réponse de $\dot{V}O_2$. Cela reste cependant à démontrer expérimentalement. Les objectifs de la présente étude étaient donc : (1) d'examiner si les évaluations précoces de $\dot{V}O_{2max}$ sous-estimaient la $\dot{V}O_2$ et (2) d'étudier si le plateau apparent de $\dot{V}O_2$ observé dans les études classiques était un artefact de mesure représentant un état non stationnaire.

Résumé des faits et des résultats:

Douze sujets de sexe masculin (28 ± 7 ans, 1,78 ± 0,05 m, 80 ± 11 kg) ont chacun effectué un test incrémental par paliers à vitesse constante de pédalage. Ce protocole visait à reproduire le test par paliers à incréments constants utilisé par Taylor. Les données de $\dot{V}O_2$ ont été moyennées pendant l'intervalle de temps 1.75-2.75 min ($\dot{V}O_{2.Taylor}$) et à la minute finale de chaque test ($\dot{V}O_{2.Finale}$). Un test t pour échantillons appariés a été utilisé pour évaluer les différences de $\dot{V}O_{2pic.Taylor}$ et de $\dot{V}O_{2pic.Finale}$.

La $\dot{V}O_{2peak.Finale}$ s'est révélée significativement plus élevée que la $\dot{V}O_{2peak.Taylor}$ (P <0,001, d = 1,18). La pente de la réponse de $\dot{V}O_2$, calculée à partir du dernier icrément obtenu chez chaque participant était significativement différente de zéro pendant les intervalles 1,75-2,75 min (Taylor: P = 0,009, d = 1,58, Final: P = 0,02, d = 0,29).

Conclusion

Ces données indiquent que le plateau de $\dot{V}O_2$ décrit dans les études historiques était très probablement un artefact. Des recherches plus approfondies, évitant de se baser sur les présupposés vraisemblablement erronés des études historiques, pourraient permettre aux physiologistes de l'exercice et aux praticiens de déterminer quelle combinaison de protocole d'exercice et de méthode d'acquisition de données est la plus propice à l'induction et à la détection d'un authentique plateau de $\dot{V}O_2$.

Mots-clés: Exercice maximal; Consommation d'oxygène; Plateau;

2.0 Introduction

The concept and existence of maximal oxygen uptake ($\dot{V}O_{2max}$) remains a contemporary and contentious topic of debate [2-4]. Central to this debate (and indeed concept of $\dot{V}O_{2max}$) is $\dot{V}O_2$ plateau, it being the only objective criteria to indicate the attainment of $\dot{V}O_{2max}$.

Much debate has focussed on whether $\dot{V}O_{2max}$ or plateau was achieved in historical studies. The use of short discontinuous tests (DCT), as opposed to modern ramp tests, was used commonly [1,5,6] to investigate $\dot{V}O_{2max}$. Taylor, et al. [1] was the first study to detect $\dot{V}O_2$ plateau in a large number of participants and has been asserted as empirical evidence that $\dot{V}O_2$ during progressive exercise meets a limit that cannot be exceeded. Taylor, et al. [1] compared two DCT protocols using a motorised treadmill to assess $\dot{V}O_{2max}$. The first of these tests used the Hill model of incremental speed increases at a predetermined gradient (n=13) [5,6]. The second comprised incremented gradient increases (2.5%) at a constant speed (11.3 km.h^{-1}) (n=115) [5,6].

The advent of breath-by-breath analysis, providing greater insight into the time course of oxygen uptake ($\dot{V}O_2$ kinetics) [7,8], raises questions as to whether apparent plateau in classical studies was in fact artefactual, and indicative of measuring $\dot{V}O_2$ in the non-steady (dynamic) state [2-4,9]. However, debate has focussed on re-examination of published data from classic studies [5,6], rather than use breath-by-breath analyses to provide clear, empirical evidence.

In contemporary debate, the seminal works of A.V. Hill and colleagues [5,6] have been used to evidence the existence, or otherwise, of $\dot{V}O_2$ plateau [2-4]. However, this work is empirically irreproducible due to the variable speeds and collection periods utilised [5,6]. However, the work of Taylor, et al. [1], who utilised motorised treadmills, fixed collection periods and reported higher incidences of $\dot{V}O_2$ plateau, would enable successful replication. Further, results obtained through replicating Taylor, et al. [1] would be equally applicable to those of A. V. Hill and colleagues, as it is likely $\dot{V}O_2$ was still measured in the non-steady state.

In Taylor, et al. [1], participants were required to run for 3 min; expired gas was then collected between 1.75-2.75 min. This timing was rationalized with the explanation that mean $\dot{V}O_2$ did not increase when gas was collected between 2 min 45 s and 3 min 45 s (3.48 L.min^{-1} vs. 3.45 L.min^{-1}). However, these values were not taken from the full sample. The treadmill gradient was increased by increments of 2.5% on consecutive days until either a $\dot{V}O_2$ plateau was detected or the participant failed to complete 3 min. This makes Taylor, et al. [1] a suitable study to replicate in order to investigate incidence of plateau in historical studies.

A clear answer as to whether $\dot{V}O_2$ was artefactual in classic studies would enable contemporary debate to move on. Therefore, the aims of the present study were (1) to investigate whether early $\dot{V}O_{2max}$ assessments underestimated actual $\dot{V}O_2$, and (2) to investigate whether the apparent $\dot{V}O_2$ plateau observed in classic studies was an artefact of measuring in a non-steady state.

3.0 Methods

3.1 Participants

Twelve male recreationally active participants (mean ± SD; age 28 ± 7 y, height 1.78 ± 0.05 m, mass 80 ± 11 kg) volunteered to participate in this study, which had been approved by the institutional research ethics committee. Written and informed consent was obtained prior to data collection. Participants were instructed to report to the laboratory in a well-hydrated, rested state, and having abstained from alcohol, and caffeine for the preceding 24 h and 6 h, respectively. This study conformed to the Declaration of Helsinki.

3.2 Protocol

Participants visited one-of-two laboratories, with identical equipment, to perform a DCT on a motorised treadmill (Ergo ELG 70, Woodway GmbH, Weil & Rhein, Germany), for the determination of $\dot{V}O_{2peak}$ and $\dot{V}O_2$ plateau. The test started at 11.3 $km.h^{-1}$ and a 0% gradient, and consisted of 8 min stages of running at increased gradient (2.5% increments) until volitional exhaustion, with no more than two transitions performed in a 24-hour period. The test was terminated when the participant was unable to perform a minimum of 3 min exercise at a given stage. Participants were instructed to perform maximally and to maintain the exercise for as long as possible.

During the DCT test, participants wore a nose clip and breathed through a low-dead-space (90 mL), low-resistance (5.5 cmH_2O at 510 $L.min^{-1}$) mouthpiece and impeller turbine transducer assembly (Jaeger Triple V, Jaeger GmbH, Hoechburg, Germany). Inspired and expired gas volume and concentration signals were continuously sampled (at 100 Hz) and drawn from the mouthpiece through a 2-m sampling line (0.5 mm internal diameter) to paramagnetic (O_2) and infrared (CO_2) analysers (Jaeger Oxycon Pro, Hoechburg, Germany).

3.3 Data Analyses

The breath-by-breath $\dot{V}O_2$ data were initially examined to exclude errant breaths caused by coughing, swallowing etc., and those values lying more than 4 SD from the local mean were removed [10]. Subsequently, the breath-by-breath data were interpolated to second-by-second data and time aligned to the start of exercise.

The $\dot{V}O_{2peak}$ was calculated as the highest 60-s sequential average. $\dot{V}O_2$ was also determined between 1.75-2.75 min for comparison to the findings in the sample of Taylor, et al. [1]. Plateau was subsequently defined as a change in $\dot{V}O_2$ of $<150ml.min^{-1}$ or $<2.1ml.kg^{-1}.min^{-1}$ between successive stages during the incremental stages [1]. Thus, an 80% confidence interval was actually used to determine $\dot{V}O_2$ plateau, according to Taylor's criteria [1]. Using this approach, a plateau in the $\dot{V}O_2$ treadmill gradient relationship was evident and produced plateau in 69% of the participants using the continuous Hill approach and in 94% (108 of 115) of participants using the discontinuous approach [5,6].

3.4 Statistical analyses

Linear regression was used to determine the slope of the $\dot{V}O_2$ response and was determined for 1.75-2.75 min, and over the final minute of each DCT stage. A one-sample *t*-test was used to compare the slope of the $\dot{V}O_2$ response derived from the regression analysis. A paired-sample *t*-test was used to compare $\dot{V}O_{2peak}$ derived from the criteria of Taylor [1] and final collection. Statistical significance was set as $P < 0.05$, and effect sizes were reported using Cohen's d [11]. Data were presented as mean ± SD unless otherwise stated.

4.0 Results

The $\dot{V}O_{2peak.Final}$ was found to be significantly higher than $\dot{V}O_{2peak.Taylor}$ (Table 1.) ($P<0.001$, $d = 1.18$). The slope of the $\dot{V}O_2$ response, calculated from the last completed gradient for each participant was significantly different from zero during the 1.75-2.75 min (Taylor: $P=0.009$, $d = 1.58$; Final: $P=0.02$, $d = 0.29$). Incidence of a $\dot{V}O_2$ plateau ($\Delta\dot{V}O_2$ of $<150ml{\cdot}min^{-1}$ or $<2.1ml{\cdot}kg^{-1}{\cdot}min^{-1}$ between increments) was observed in 7 of 12 participants (58%), with some demonstrating multiple instances of plateau. Each participant successfully completed an additional increment and achieved higher $\dot{V}O_2$ following observation of a plateau.

Table 1 about here

Figure 1 about here

5.0 Discussion

The principal findings of this investigation were that in classic studies [1], measured $\dot{V}O_{2peak}$ could not have been $\dot{V}O_{2max}$, and, apparent plateau was clearly artefactual.

Taylor, et al. [1] considered measurement of $\dot{V}O_2$ beyond 3 minutes to have no perceivable benefit, and similarly short collection periods were utilised by Hill and colleagues [5,6]. The present study sought to demonstrate that when stage length was increased or higher intensities were attempted, a higher $\dot{V}O_2$ would be shown and these data clearly demonstrate a higher $\dot{V}O_2$ is achieved, if stages are extended. Highlighting the fact that short stages will be measuring $\dot{V}O_2$ in the non-steady state, which is the cause of the artefactual plateau.

Taylor, et al. [1] was a pragmatic study to replicate due to the high variability in speed and collection periods reported in Hill and colleagues [5,6], whilst Taylor, et al. [1] utilised motorised treadmills, uniform collection periods and reported high incidence of plateau. However, findings of the present study would be equally applicable to A. V. Hill and colleagues, as it is likely $\dot{V}O_2$ was still measured in the non-steady state. The advent of breath-by-breath analyses has enabled far greater scrutiny of whether $\dot{V}O_{2max}$ is achieved, thereby allowing demonstration of an artefactual $\dot{V}O_2$ plateau.

This study has not sought to add to clarification of the existence, or otherwise, of $\dot{V}O_2$ plateau (and by definition, $\dot{V}O_{2max}$), and cannot comment on mechanistic action. This study has, however, clearly demonstrated that $\dot{V}O_2$ plateau in historical studies was artefactual [1]. It is evident that contemporary debate needs to move on, with little value in re-examination of, and referral to this historical work. Further investigation without the fallacious assumptions of historical studies may enable exercise physiologists and practitioners to determine which combination of exercise protocol and method of data acquisition is most conducive to elicit and detect a $\dot{V}O_2$ plateau.

6.0 References

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7.0 Figure Captions

Figure 1. Individual participant plot for the same increment showing the measured $\dot{V}O_2$ response to an exhaustive treadmill run. The individual slopes of $\dot{V}O_{2.Taylor}$ (a) and $\dot{V}O_{2.Final}$ (b) have been demarcated *(bold lines)*, and for the last completed increment lasting approximately 3.5 min. This shows the measured $\dot{V}O_2$ response to an exhaustive treadmill run and the slope of $\Delta\dot{V}O_2$ during $\dot{V}O_{2.Taylor}$ (c) and $\dot{V}O_{2.Final}$ (d).

8.0 Tables

Table 1. Group data obtained from the final constant-speed treadmill runs.

Parameter	Taylor	Final
$\dot{V}O_2$ ($ml \cdot min^{-1}$)	4109 ± 310	4480 ± 509*
Slope ($ml \cdot min^{-2}$)	231 ± 146#	35 ± 123‡

* Significantly different from *Taylor* ($P<0.001$, $d = 1.18$). # Significantly different from 0 ($P=0.009$, $d = 1.58$). ‡ Significantly different from 0 ($P=0.02$, $d = 0.29$).

9.0 Figures

FIGURE 1.