

Artefactual Incidence of VO₂ Plateau and VO₂max in Historical Studies: Time to Move on

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34 **1.0 Summary (English)**

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

36 Purpose

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

43 Summary of Facts and Results

44 Twelve males (age 28 ± 7 y, 1.78 ± 0.05 m, 80 ± 11 kg) each completed a constant speed
45 discontinuous test. The study design replicated the increasing gradient discontinuous test used
46 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
47 the final minute of each test ($\dot{V}O_{2.Final}$). A paired samples *t*-test was used to evaluate differences
48 in $\dot{V}O_{2peak.Taylor}$ and $\dot{V}O_{2peak.Final}$

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

53

54 Conclusion

55 $\dot{V}O_2$ plateau in historical studies was artefactual. Further investigation, without the fallacious
56 assumptions of historical studies, may enable exercise physiologists and practitioners to
57 determine which combination of exercise protocol and method of data acquisition is most
58 conducive to elicit and detect a $\dot{V}O_2$ plateau.

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

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

73 **Résumé (Français)**

74 **Introduction**

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

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83 **Résumé des faits et des résultats:**

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

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92 **La $\dot{V}O_{2peak.Finale}$ s'est révélée significativement plus élevée que la $\dot{V}O_{2peak.Taylor}$ ($P < 0,001$,**
93 **$d = 1,18$). La pente de la réponse de $\dot{V}O_2$, calculée à partir du dernier incrément obtenu**
94 **chez chaque participant était significativement différente de zéro pendant les intervalles**
95 **1,75-2,75 min (Taylor: $P = 0,009$, $d = 1,58$, Final: $P = 0,02$, $d = 0,29$).**

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98 **Conclusion**

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

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

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111 2.0 Introduction

112 The concept and existence of maximal oxygen uptake ($\dot{V}O_{2\max}$) remains a contemporary and
113 contentious topic of debate²⁻⁴. Central to this debate (and indeed concept of $\dot{V}O_{2\max}$) is $\dot{V}O_2$
114 plateau, it being the only objective criteria to indicate the attainment of $\dot{V}O_{2\max}$.

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

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

128 In contemporary debate, the seminal works of A.V. Hill and colleagues^{5,6} have been used to
129 evidence the existence, or otherwise, of $\dot{V}O_2$ plateau²⁻⁴. However, this work is empirically
130 irreproducible due to the variable speeds and collection periods utilised^{5,6}. However, the work
131 of Taylor, et al.¹, who utilised motorised treadmills, fixed collection periods and reported
132 higher incidences of $\dot{V}O_2$ plateau, would enable successful replication. Further, results obtained
133 through replicating Taylor, et al.¹ would be equally applicable to those of A. V. Hill and
134 colleagues, as it is likely $\dot{V}O_2$ was still measured in the non-steady state.

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

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

147 3.0 Methods

148 3.1 Participants

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

155 3.2 Protocol

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

164 During the DCT test, participants wore a nose clip and breathed through a low-dead-space (90
165 mL), low-resistance (5.5 cmH₂O at 510 L.min⁻¹) mouthpiece and impeller turbine transducer
166 assembly (Jaeger Triple V, Jaeger GmbH, Hoechburg, Germany). Inspired and expired gas
167 volume and concentration signals were continuously sampled (at 100 Hz) and drawn from the
168 mouthpiece through a 2-m sampling line (0.5 mm internal diameter) to paramagnetic (O₂) and
169 infrared (CO₂) analysers (Jaeger Oxycon Pro, Hoechburg, Germany).

170 3.3 Data Analyses

171 The breath-by-breath $\dot{V}O_2$ data were initially examined to exclude errant breaths caused by
172 coughing, swallowing etc., and those values lying more than 4 SD from the local mean were
173 removed¹⁰. Subsequently, the breath-by-breath data were interpolated to second-by-second
174 data and time aligned to the start of exercise.

175 The $\dot{V}O_{2\text{peak}}$ was calculated as the highest 60-s sequential average. $\dot{V}O_2$ was also determined
176 between 1.75-2.75 min for comparison to the findings in the sample of Taylor, et al.¹. Plateau
177 was subsequently defined as a change in $\dot{V}O_2$ of <150ml.min⁻¹ or <2.1ml.kg⁻¹.min⁻¹ between
178 successive stages during the incremental stages¹. Thus, an 80% confidence interval was
179 actually used to determine $\dot{V}O_2$ plateau, according to Taylor's criteria¹. Using this approach,
180 a plateau in the $\dot{V}O_2$ treadmill gradient relationship was evident and produced plateau in 69%
181 of the participants using the continuous Hill approach and in 94% (108 of 115) of participants
182 using the discontinuous approach^{5,6}.

183 3.4 Statistical analyses

184 Linear regression was used to determine the slope of the $\dot{V}O_2$ response and was determined for
185 1.75-2.75 min, and over the final minute of each DCT stage. A one-sample *t*-test was used to
186 compare the slope of the $\dot{V}O_2$ response derived from the regression analysis. A paired-sample
187 *t*-test was used to compare $\dot{V}O_{2\text{peak}}$ derived from the criteria of Taylor¹ and final collection.
188 Statistical significance was set as $P < 0.05$, and effect sizes were reported using Cohen's *d*¹¹.
189 Data were presented as mean \pm SD unless otherwise stated.

190 4.0 Results

191 The $\dot{V}O_{2\text{peak.Final}}$ was found to be significantly higher than $\dot{V}O_{2\text{peak.Taylor}}$ (Table 1.) ($P < 0.001$, d
192 = 1.18). The slope of the $\dot{V}O_2$ response, calculated from the last completed gradient for each
193 participant was significantly different from zero during the 1.75-2.75 min (Taylor: $P = 0.009$, d
194 = 1.58; Final: $P = 0.02$, $d = 0.29$). Incidence of a $\dot{V}O_2$ plateau ($\Delta\dot{V}O_2$ of <150ml.min⁻¹ or
195 <2.1ml.kg⁻¹.min⁻¹ between increments) was observed in 7 of 12 participants (58%), with some
196 demonstrating multiple instances of plateau. Each participant successfully completed an
197 additional increment and achieved higher $\dot{V}O_2$ following observation of a plateau.

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200 **Table 1 about here**

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202 **Figure 1 about here**

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204 **5.0 Discussion**

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

207 Taylor, et al. ¹ considered measurement of $\dot{V}O_2$ beyond 3 minutes to have no perceivable
208 benefit, and similarly short collection periods were utilised by Hill and colleagues ^{5,6}. The
209 present study sought to demonstrate that when stage length was increased or higher intensities
210 were attempted, a higher $\dot{V}O_2$ would be shown and these data clearly demonstrate a higher $\dot{V}O_2$
211 is achieved, if stages are extended. Highlighting the fact that short stages will be measuring
212 $\dot{V}O_2$ in the non-steady state, which is the cause of the artefactual plateau.

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

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

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240 **6.0 References**

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281 **7.0 Figure Captions**

282 **Figure 1.** Individual participant plot for the same increment showing the measured $\dot{V}O_2$
283 response to an exhaustive treadmill run. The individual slopes of $\dot{V}O_{2.Taylor}$ (a) and $\dot{V}O_{2.Final}$ (b)
284 have been demarcated (*bold lines*), and for the last completed increment lasting approximately
285 3.5 min. This shows the measured $\dot{V}O_2$ response to an exhaustive treadmill run and the slope
286 of $\Delta\dot{V}O_2$ during $\dot{V}O_{2.Taylor}$ (c) and $\dot{V}O_{2.Final}$ (d).

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312 **8.0 Tables**

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

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

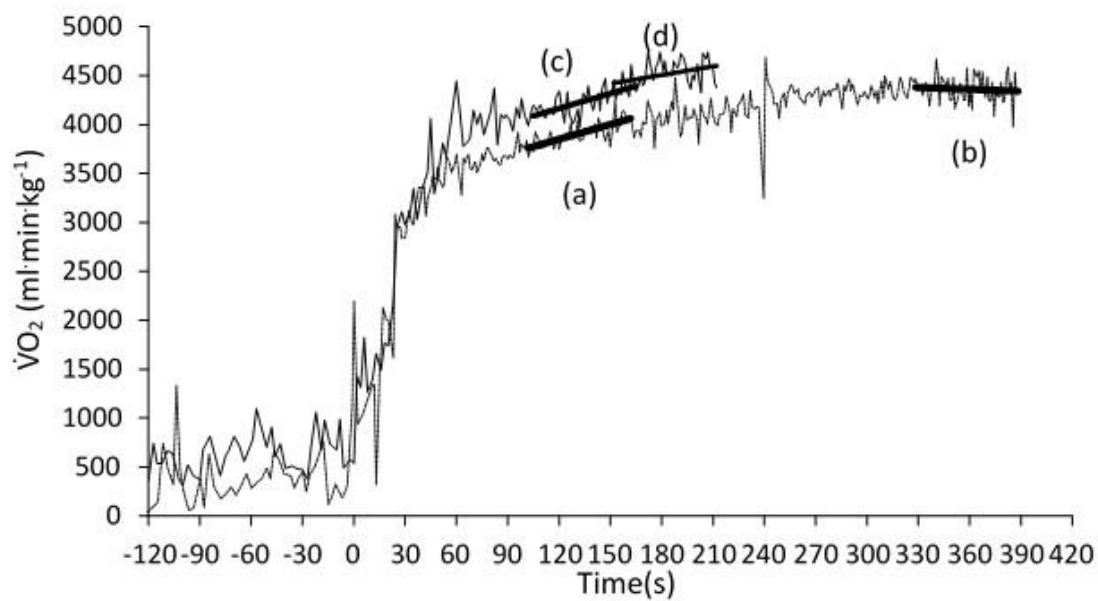
314 * Significantly different from *Taylor* ($P < 0.001$, $d = 1.18$). # Significantly different from
315 0 ($P = 0.009$, $d = 1.58$). ‡ Significantly different from 0 ($P = 0.02$, $d = 0.29$).
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340 **9.0 Figures**

341 **FIGURE 1.**



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