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ORIGINAL ARTICLE

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Low frequency of the "plateau phenomenon" during maximal exercise in elite British athletes

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Abstract A plateau in oxygen consumption ($\dot{V}O_2$) has long been considered the criterion for maximal effort during an incremental exercise test. But, surprisingly, the termination of a maximum exercise test often occurs in the absence of a $\dot{V}O_2$ plateau. To explain this inconsistency, some have proposed that an oxygen limitation in skeletal muscle occurs only in elite athletes. To evaluate this hypothesis, we determined the frequency with which the "plateau phenomenon" developed in a group of elite male and female athletes. Fifty subjects performed a continuous incremental treadmill test to measure maximal oxygen consumption ($\dot{V}O_{2max}$). Treadmill velocity increased by 0.31 m s^{-1} until the respiratory exchange ratio (R) reached 1.00. Thereafter the treadmill gradient increased by 1% each minute until exhaustion. The $\dot{V}O_{2max}$ was the highest $\dot{V}O_2$ sustained for 60 s. Three criteria were used to determine maximal efforts: (1) a plateau in the $\dot{V}O_2$, defined as an increase of less than 1.5 ml kg^{-1} min^{-1}; (2) a final R of 1.1 or above; (3) a final heart rate (HR) above 95% of the age-related maximum. Mean $\dot{V}O_{2max}$ exceeded 65 ml kg^{-1} min^{-1} in both groups. The criteria for R and HR were satisfied by 72% of males and 56% females, and 55% of males and 69% of females, respectively. In contrast a $\dot{V}O_2$ plateau was identified in only 39% of males and 25% of females. These findings refute the twin arguments: (1) that the absence of a "plateau phenomenon" results from an inadequate motivational effort in poorly trained athletes and (2) that the "plateau phenomenon" and a consequent skeletal muscle anaerobiosis occur only in athletes with the highest $\dot{V}O_{2max}$ values.

Keywords Maximum oxygen consumption · Plateau phenomenon · Olympic athletes · Motivation · Anaerobiosis

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Introduction

A popular criterion for the attainment of maximal effort during a progressive exercise test to exhaustion is the development of a levelling off or "plateau" in oxygen consumption ($\dot{V}O_2$) (Bassett and Howley 1997, 2000; Mitchell and Blomqvist 1971; Sloniger et al. 1996; Taylor et al. 1955; Wagner 2000; Wyndham et al. 1959). It is argued that beyond the "plateau", the additional energy provision is by "anaerobic metabolism" (Bassett and Howley 1997, 2000; Wyndham et al. 1959) according to the original postulate of Hill and his colleagues (Hill et al. 1924a, 1924b). Thus the presence of the plateau phenomenon is a necessary component of the theory that maximal exercise terminates as a result of anaerobiosis in the active skeletal muscles (Noakes 1988, 1997, 1998).

A surprising finding is that not all subjects volitionally terminate a maximum exercise test in the presence of a clearly defined and unambiguous plateau phenomenon. Whereas the original studies, in which exercise testing was performed intermittently over a period of several days, showed the presence of a clearly defined plateau phenomenon in between 50% and 94% of subjects (Astrand 1952; Taylor et al. 1955), more modern studies using a single, progressive, uninterrupted test to exhaustion have identified the "plateau phenomenon" in a smaller proportion of subjects (Armstrong et al. 1995, 1998; Cunningham et al. 1977; Draper et al. 1999; Duncan et al. 1997; Myers et al. 1989, 1990; Sheehan et al. 1987; St Clair Gibson et al. 1999), sometimes as low as 0–33% (Draper et al. 1999; Froelicher et al. 1974;

Hartling et al. 1989; Niemelä et al. 1980; Rowland 1993; Rowland and Cunningham 1992; Taylor 1941), depending on the criteria used in the definition.

To explain this anomaly, some have suggested that only ‘‘highly fit’’ athletes (Dempsey and Wagner 1999) with larger values for maximum oxygen consumption ($\dot{V}O_{2max}$), usually in excess of 65 ml kg^{-1} min^{-1}, are likely to develop an oxygen limitation at maximal exercise. The basis for this hypothesis is the finding that arterial desaturation is more likely to occur in athletes of this calibre (Dempsey and Wagner 1999).

To evaluate this hypothesis, we determined the frequency with which the plateau phenomenon developed in a group of elite male and female athletes undergoing physiological evaluation at the British Olympic Medical Centre at Northwick Park Hospital in Middlesex. In order to be selected for evaluation at the Centre, athletes had to achieve, or be considered capable of achieving an Olympic qualifying performance. This ensured that only the very best British athletes of international class were evaluated. We expected that the majority of these athletes would have $\dot{V}O_{2max}$ values in excess of 65 ml kg^{-1} min^{-1}, therefore increasing the likelihood that they would develop a limiting oxygen utilization during maximal exercise, according to a current hypothesis (Dempsey and Wagner 1999; Wagner 2000).

Methods

A total of 34 men and 16 women middle and long distance runners who competed in events from 800 m to the marathon were tested as part of their preparation for the Olympic Games. All subjects were from one of two categories as designated by the British Olympic Association: category A—present Great Britain squad member and probable Olympic representative, or category B—present international and possible Olympic representative. Two of the male subjects were former world record holders. Details of the subjects are described in Table 1 and personal best performance within a period of 2 months prior to the testing is described in Table 2.

A continuous incremental treadmill test was performed to measure $\dot{V}O_{2max}$. Electrodes were positioned in the CM-5 lead placement and connected to a Rigel 302 Cardiometer (Surrey, UK). Subjects were connected to a low resistance Hans-Rudolph (Kansas City, Missouri, USA) high velocity respiratory valve (2700 series) that was supported with appropriate headgear. Oxygen uptake was obtained from an on-line, computerized metabolic system (Jaeger, EOS Sprint, Jaeger, Market Harborough, UK) that incorporates a mixing bag with self-adjusting volume to maintain constant mixing time, Jaeger gas analyzers and a Jaeger pneumotachograph. Calibration gases were certified against a primary gravimetric standard. Expired air was analyzed continuously and results were calculated and expressed in 30-s time periods.

Table 1 Anthropomorphic characteristics of elite male and female British athletes. Data are means (SD)

	Male ($n=35$)	Female ($n=16$)
Age (years)	24.6 (4.5)	24.3 (3.4)
Stature (cm)	178.4 (6.3)	165.6 (6.3)*
Body mass (kg)	66.6 (5.7)	53.3 (4.0)*

*Significantly different from men, $P<0.001$

Table 2 Personal best performances (s) of elite male and female British athletes within 2 months of testing. Data are means (SD)

	Male	Female
800 m	110.4 (2.1) $n=12$[a]	125.1 (3.1) $n=8$
1,500 m	225.3 (6.6) $n=17$	257.3 (4.8) $n=12$
1 mile (I,600 m)	242.4 (5.8) $n=12$	276.0 (7.0) $n=6$
3,000 m	487.4 (11.9) $n=13$	552.2 (12.1) $n=8$
5,000 m	833.0 (18.9) $n=9$	948.0 $n=1$
10,000 m	1,754.0 (48.1) $n=8$	2,007.2 (177.6) $n=2$
42.2 km	8,350.0 (194.7) $n=3$	–

[a]Number of runners with a personal best time for the given distance

All subjects were familiarized with the test protocol that included a 5-min warm-up on a treadmill (Powerjog, Birmingham, UK), the belt speed of which was calibrated prior to testing with a 1-m distance measuring wheel (Trumeter, Manchester, UK) and stopwatch. The gradient of the treadmill was calibrated by the tangent method with a carpenter's square and level. The test began at zero gradient and a velocity of 3.2 m s^{-1} (186 m min^{-1}) for both males and females. Initially treadmill speed was increased by 0.31 m s^{-1} (16 m min^{-1}) every minute until the respiratory exchange ratio (R) had reached a value of 1.00. This occurred at approximately 4.72 m s^{-1} (282 m min^{-1}) and 5.33 m s^{-1} (309 m min^{-1}) in females and males respectively. These running velocities are approximately the same as those used by Daniels and Daniels (1992) who also tested Olympic class athletes. Once this velocity had been attained, it was held constant and the gradient was increased by 1% each minute until volitional exhaustion. The $\dot{V}O_{2max}$ was recorded as the highest $\dot{V}O_2$ that the subjects could sustain for the duration of a work interval, which was 60 s.

Three criteria were used to determine maximal efforts:

1. A plateau or levelling-off in the oxygen uptake was defined as an increase of oxygen uptake of less than 1.5 ml kg^{-1} min^{-1} or successive values within 5% of each other (Davies 1968; Niemelä et al. 1980) despite progressive increases in exercise intensity produced by the 1% increase in treadmill gradient every 60 s. $\dot{V}O_2$ increases approximately 3.5 ml kg^{-1} for every 2.5% gradient elevation (Balke 1954).
2. A final R of 1.1 or above (Issekutz 1962).
3. A final heart rate (HR) above 95% of the age-related maximum (Maritz 1961).

Statistical analyses

All test results were entered into the data entry program of the Statistical Package for the Social Science (SPSS-X PC, Chicago, USA). Comparison of males' and females' criteria measurements were determined by Student's t-test for independent data. Linear correlations between parameters were determined by Pearson's product moment.

Results

Means (SEM) for selected anthropomorphic, best running performances, and physiological responses to maximal exercise are given in Tables 1, 2, 3. As expected, men were significantly taller and heavier than the women (Table 1) and performed better at all running distances (Table 2).

Men had significantly higher $\dot{V}O_{2max}$ values expressed in either litres per minute, or when scaled to body dimensions, in millilitres per minute per two-thirds of a

Table 3 Selected physiological responses in elite male and female British athletes during maximum exercise testing. Data are means (SEM). $\dot{V}O_{2max}$ Maximum rate of O_2 consumption; *R* respiratory exchange ratio; HR heart rate

	Male ($n=34$)	Female ($n=16$)
$\dot{V}O_{2max}$ (l min^{-1})	5.26 (0.80)	3.52 (0.80)*
$\dot{V}O_{2max}$ (ml min^{-1} $kg^{-2/3}$)	319.5 (3.1)	248.4 (4.4)*
$\dot{V}O_{2max}$ (ml min^{-1} kg^{-1})	79.1 (0.7)	66.1 (1.2)*
Maximum *R*	1.11 (0.10)	1.11 (0.20)
Maximum HR (beats min^{-1})	185.0 (1.2)	182.0 (2.4)
$\dot{V}O_2$ difference (ml min^{-1} kg^{-1}) for final two stages	2.49 (0.24)	2.02 (0.27)

*Different from males $P<0.001$

Table 4 Number of athletes satisfying attainment criteria for a maximum effort

	$\dot{V}O_2$ plateau[a]	HR[b]	*R*[c]
Males ($n=36$)	14 (39%)	17 (45%)	26 (72%)
Females ($n=16$)	4 (25%)	5 (31%)	9 (56%)

[a]An increase in $\dot{V}O_2$ of less than 1.5 ml kg^{-1} min^{-1} from penultimate to ultimate exercise stage
[b]Maximum HR≥95% age-predicted maximum
[c]Maximum$R>1.1$

kilogram or millilitres per minute per kilogram (Table 3). Mean $\dot{V}O_{2max}$ values exceeded 65 ml min^{-1} kg^{-1} in both groups. Neither maximum *R* nor maximum HR was different between males and females. In both groups, the mean $\dot{V}O_2$ increase for the final two exercise stages exceeded 2 ml min^{-1} kg^{-1} and was not different between males and females.

Table 4 describes the percentage of athletes who fulfilled the different criteria for a maximum effort. Whereas 72% of males and 56% of females satisfied the *R* criteria for maximal effort, fewer (55% of males and 69% of females) attained the HR criteria (95% of their age-predicted maximum HR).

In contrast only 39% of males and 25% of females achieved the levelling-off criteria in $\dot{V}O_2$ sufficient to suggest that they had shown a "plateau phenomenon" according to the concept originally proposed by Taylor et al. (1955).

Discussion

To the best of our knowledge, this study is the first to address the frequency with which the plateau phenomenon develops in a group of highly trained, elite athletes of Olympic calibre. Most of the previous studies have evaluated this phenomenon in healthy subjects of varying, but usually modest, athletic ability.

Indeed the $\dot{V}O_{2max}$ values for men and women reported here are generally higher than those of "elite" athletes reported elsewhere (Hoogeveen and Hoogsteen 1999; Lucia et al. 1999; Nieman et al. 1999; Warburton et al. 1999) but almost identical to those measured by Daniels and Daniels (1992), who also studied a sample of Olympic athletes, similar in both running performance and body composition to the athletes in the present study.

Accordingly, this group of athletes provides the ideal group to evaluate the hypothesis that, if the "plateau phenomenon" truly represents the onset of a limitation in oxygen delivery to the exercising skeletal muscles with the subsequent development of skeletal muscle anaerobiosis, then the phenomenon should be present in virtually all these high-class athletes who, it must be assumed, have the greatest potential to drive themselves into "anaerobiosis".

Furthermore, the phenomenon of arterial desaturation during maximal exercise is believed to occur most commonly in highly fit athletes with the highest $\dot{V}O_{2max}$ values (Dempsey and Wagner 1999). Indeed Wagner (2000) argues that the "plateau phenomenon" occurs only in "human and animal subjects with high pain and fatigue tolerance". The absence of the plateau phenomenon is likely in subjects whose "pain or fatigue tolerance is low" so that "the unpleasant symptoms of exhaustion, and/or leg pain result in termination of exercise with no evident plateau" (Wagner 2000).

It is of interest that this interpretation acknowledges the potential role that central (neural) drive may play in determining maximum exercise performance. This contrast with the more popular (cardiovascular/anaerobic) model (Noakes 2000), which predicts that fatigue results from peripherally located, metabolite-induced processes. We have recently provided evidence that a reduced central neural drive, acting at a subconscious level—in contrast to a neural drive that is under conscious control proposed by Wagner (2000)—may explain the progressive reduction in power output that develops during more prolonged stochastic exercise (1–3 h) which includes repeated bouts of maximal effort (Kay et al. 2001; St Clair Gibson et al. 2000).

Accordingly, the most important finding of this study was the low frequency of an identifiable "plateau phenomenon" in these high trained, competitive and motivated athletes. Indeed the low frequency (25%) of the plateau phenomenon in the female Olympic athletes is amongst the lowest incidence yet reported in adults with only four studies reporting lower percentages (20%, Draper et al. 1999; 7%, Froelicher et al. 1974; 8–22%, Niemelä et al. 1980; 10%, Taylor 1941). This finding is at variance with the popular contention that it is a "lack of motivation" (Wagner 2000) that explains the low frequency of the plateau phenomenon.

Rather we show the opposite; that athletes with the greatest aerobic capacity and the highest motivation to achieve high $\dot{V}O_{2max}$ values have amongst the lowest frequency of "plateau phenomenon", yet reported. This would seem to disprove the contention that the absence of a "plateau phenomenon" indicates that the athlete was unwilling to motivate him or herself for a maximum effort. Rather, these data suggest that a different explanation is required.

In conclusion, this study shows that athletes with amongst the highest $\dot{V}O_{2max}$ values yet reported in a group of elite athletes, and with high motivation and superior exercise capacity, have amongst the lowest frequency of "plateau phenomenon" yet reported. This finding is inconsistent with the claim that the absence of the "plateau phenomenon" during maximum exercise reflects an absence of motivation and the inability of the tested athlete to produce a maximal effort. It is also contrary to the belief that skeletal muscle anaerobiosis is more likely to develop in athletes with the highest $\dot{V}O_{2max}$ values, who are more likely to exceed their cardiorespiratory limitations for oxygen transport (Dempsey et al. 1984).

Clearly there is a need to understand better the physiological basis for the "plateau phenomenon" (Myers et al. 1989, et al. 1990; Noakes 1988, 1997, 1998) and not simply to ascribe it to phenomena that have yet to be rigorously evaluated (Wagner 2000).

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