$\dot{V}O_{2max}$, Protocol Duration, and the $\dot{V}O_2$ Plateau

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ABSTRACT

YOON, B., L. KRAVITZ, and R. ROBERGS. $\dot{V}O_{2max}$, Protocol Duration, and the $\dot{V}O_2$ Plateau. *Med. Sci. Sports Exerc.*, Vol. 39, No. 7, pp. 1186–1192, 2007. **Purpose:** The purpose of this study was to compare $\dot{V}O_{2max}$, $\dot{V}O_2$–time slopes at the end of the protocol (last 30 s), and the presence of a $\dot{V}O_2$ plateau ($\dot{V}O_2$–time slope < 0.05 $L \cdot min^{-1}$ during the last 30 s) across four protocol durations (5, 8, 12, and 16 min) during incremental cycling exercise to $\dot{V}O_{2max}$. **Methods:** Eight male (23.8 ± 3.2 yr) and eight female (26.0 ± 8.9 yr) subjects of moderate to high fitness levels participated in the study. **Results:** $\dot{V}O_{2max}$ was significantly higher in men than in women for each protocol duration, with main effect means of 4.23 versus 2.84 $L \cdot min^{-1}$, respectively. For women, $\dot{V}O_{2max}$ did not differ between any protocol duration. For men, $\dot{V}O_{2max}$ for the 8-min protocol (4.44 ± 0.39 $L \cdot min^{-1}$) was significantly higher than for all other protocol durations. Analysis of covariance, using the highest $\dot{V}O_{2max}$ as the covariate, removed all protocol-duration significance for men. The $\dot{V}O_2$ slope for the final 30 s of each test was significantly lower for the 16-min protocol compared with the 5-min protocol, for both men and women. The ventilation threshold across four protocols was similar, at approximately 76% of $\dot{V}O_{2max}$ for both men and women. **Conclusions:** The protocol duration of tests to $\dot{V}O_{2max}$ should be between 8 and 10 min for healthy, moderately to highly trained subjects. **Key Words:** INCREMENTAL EXERCISE, MAXIMAL POWER OUTPUT, VENTILATION THRESHOLD, CYCLE ERGOMETER

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The maximal rate of oxygen consumption ($\dot{V}O_{2max}$) is one of the most commonly measured parameters in the basic and applied physiological sciences. The measure has a history dating back to 1923 and to the pioneering work of Hill and Lupton (16). Subsequent testing of $\dot{V}O_{2max}$ during the pre–World War II era was characterized by intermittent exercise protocols, typically distributed over several days (16,25). This was attributable to the limited control of the exercise equipment used and the tedious process of chemically analyzing the gas content of expired air. In fact, initial research validation of continuous exercise protocols did not occur until after 1960 (6,8,22,23), with the advent and widespread use and acceptance of electronic expired gas analysis, which allows nearly instantaneous determination of expired gas fractions.

The introduction of continuous exercise testing led to the development and validation of numerous protocols for testing $\dot{V}O_{2max}$ (13). Such protocols varied in their stage duration and increment, as well as total test duration. For example, Froelicher et al. (15) compared three different maximal exercise protocols (Bruce, Balke, and Taylor) with 15 subjects. The protocol duration across the three protocols ranged from 3 min (Taylor discontinuous) to 31 min, with $\dot{V}O_{2max}$ being significantly higher with the Taylor protocol than with either of the Bruce and Balke protocols (47.4, 44.3, and 42.8 $mL \cdot kg^{-1} \cdot min^{-1}$, respectively). Pollock et al. (23) compared four different protocols (Balke, Bruce, Ellestad, and modified Astrand) ranging from 8 (modified Astrand) to 20 min (Balke), with 55 subjects. The only difference in $\dot{V}O_{2max}$ was between the modified Astrand and Balke protocols (47.4 vs 44.1 $mL \cdot kg^{-1} \cdot min^{-1}$, respectively). The results of both Froelicher et al. and Pollock et al. indicate that longer-duration protocols lower $\dot{V}O_{2max}$. However, the research methods and protocol comparisons of this research were not adequate to answer the question of what protocol duration is ideal. Furthermore, at that time, the researchers were not focused on the superiority of a given protocol but, rather, on the suitability of a given protocol to match a subject's fitness and health status, the incidence of a $\dot{V}O_2$ plateau at $\dot{V}O_{2max}$, and the use of submaximal $\dot{V}O_2$ data to predict $\dot{V}O_{2max}$.

Despite additional research on protocols used to measure $\dot{V}O_{2max}$ (2,8,11,14,18), the direct research question of the ideal protocol duration to support a correct $\dot{V}O_{2max}$ measurement was not addressed until the work of Buchfuhrer (7) in 1983. In this study, 12 men (ages 39 ± 8.2 yr) completed various exercise tests using 1-min increments to exhaustion on a treadmill and a cycle ergometer. Tests (treadmill or cycle ergometry) with a protocol duration of 8–17 min had higher $\dot{V}O_{2max}$ values than if the protocol duration was greater than 17 min or less than 8 min.

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Buchfuhrer et al. recommended that the highest $\dot{V}O_{2max}$ would be obtained during incremental exercise lasting 10 ± 2 min. In addition, the Buchfuhrer et al. study has been the hallmark study in support of the widely promoted and accepted recommendation for exercise tests measuring $\dot{V}O_{2max}$ to last between 8 and 12 min.

Despite the broad acceptance of the results of Buchfuhrer et al. (7), the study had numerous flaws. For example, although starting with 12 subjects, specific protocols were performed with a subset of five subjects (age = 36 ± 9.7, treadmill $\dot{V}O_{2max}$ = 52 ± 8.4 $mL \cdot kg^{-1} \cdot min^{-1}$). On the basis of this sample size, estimation of statistical power at 80% indicated the inability to detect mean differences < 20 $mL \cdot kg^{-1} \cdot min^{-1}$ (two-tailed *t*-test, $P < 0.05$) (Statemate, GraphPad Software, San Diego, CA). Clearly, the Buchfuhrer study was inadequately designed to test the influence of protocol duration on $\dot{V}O_{2max}$, resulting in unacceptable risk for numerous type II errors.

Since the study of Buchfuhrer et al. (7), research of $\dot{V}O_{2max}$ continues to be published with relatively long protocol durations, many exceeding 20 min. In contrast, recent research on this topic has revealed that protocol durations < 8 min may support higher $\dot{V}O_{2max}$ values. For example, Lepretre (20) have demonstrated that $\dot{V}O_{2max}$ values were not different between two durations (5 min 12 s ± 2 min 25 s and 12 min 6 s ± 3 min 5 s) on a cycle ergometer in highly trained men (aged = 33 ± 7 yr). McCole et al. (21) also have shown similar results on a treadmill in healthy men (N = 6) and women (N = 3) aged 27 ± 4 yr. Astorino et al. (4) had 26 young subjects (16 men and 10 women, ages 21 ± 3 yr) perform incremental treadmill $\dot{V}O_{2max}$ tests of approximately 6-, 10-, and 14-min durations. $\dot{V}O_{2max}$ was not different between the 6- and 10-min durations, but it was significantly lower in the 14-min duration. This investigation supported that protocol durations between 6 and 12 min on a treadmill could be used for young adults.

Given the need to better assess the effect of short-duration protocols on $\dot{V}O_{2max}$, the purpose of this study was to compare $\dot{V}O_{2max}$, $\dot{V}O_2$–time slopes at the end of the protocol (last 30 s), and the presence of a $\dot{V}O_2$ plateau ($\dot{V}O_2$–time slope < 0.05 $L \cdot min^{-1}$ during the last 30 s) across four protocol durations (5, 8, 12, and 16 min) and between genders during incremental cycling exercise to $\dot{V}O_{2max}$. In addition, the role of fitness on the $\dot{V}O_{2max}$ response to protocol duration was assessed using analysis of covariance.

METHODS

Subjects. Sixteen subjects of moderate- to high-fitness endurance training status (eight men and eight women) participated in this study. Subjects were recruited from university and community cycling and triathlon teams. Potential subjects first completed a health history questionnaire to assess their risk factors. The Standard operational procedures document for the exercise physiology laboratories was explained. Subject exclusion criteria included 1) the inability to refrain from training the day before or the day of each test of $\dot{V}O_{2max}$; 2) the inability to refrain from caffeine or alcohol ingestion the day before or the day of each test; 3) exposure to altitudes < 1000 ft or > 12,000 ft during the month before the study; 4) $\dot{V}O_{2max}$ < 45 $mL \cdot kg^{-1} \cdot min^{-1}$ for men and < 40 $mL \cdot kg^{-1} \cdot min^{-1}$ for women (as assessed from initial $\dot{V}O_{2max}$ test); 5) any cardiovascular, pulmonary, or metabolic disorder; and 6) age < 18 yr, or > 40 yr for men and > 50 yr for women.

Procedures. After subjects passed the initial health history screening, the details of the study, including risks and benefits, were explained to the subjects. Subjects then signed a university-approved informed consent. Once the informed consent was signed, subjects completed a training history questionnaire and were then measured for height, weight, and three-site skinfold measurement (chest, abdomen, and thigh for males; tricep, suprailiac, and thigh for females). On the basis of the content of the training history questionnaire, a protocol (ramp function, in watts per minute) was chosen that we predicted would cause volitional fatigue between 10 and 12 min. Subjects then performed a familiarization trial to $\dot{V}O_{2max}$ on a cycle ergometer (Excalibur Sport, Corval Lode B.V., Lode Medical Technology, Groningen, The Netherlands) with breath-by-breath expired gas analysis. If a subject met the $\dot{V}O_{2max}$ and other inclusion criteria, he or she was then scheduled to visit the laboratory on two other occasions to complete the four tests of $\dot{V}O_{2max}$. Two tests were completed each day, separated by approximately 45 min of recovery. Prior research has shown that multiple tests of $\dot{V}O_{2max}$ on the same day yield valid data (11). The subjects warmed up for 10 min at 75 W before the tests, and test order was sequentially assigned to subjects in a balanced manner to control order effects.

During each test, expired air was sampled from a compliant mixing bag connected to the expired side of the mouthpiece and was analyzed by electronic analyzers (AEI Technologies, model S-3A and model CD-3H, Pittsburg, PA). Expired ventilation was quantified by a unidirectional flow turbine (L.L. Engineering Model S-430, Van Nuys, CA). Data were uploaded to a computer, and computations of expired gas analysis were performed for each breath, using custom programming (LabVIEW, National Instruments, Austin, TX). Heart rate was recorded from a three-lead electrocardiography system (Quinton 4000, Quinton, Seattle, WA) where an analog signal of heart rate from the ECG was integrated into the data-acquisition software and aligned to each breath.

Data processing. To determine $\dot{V}O_{2max}$, the data were imported into a custom-developed software program (LabVIEW, National Instruments, Austin, TX). The data were analyzed by a Butterworth third-order low-pass digital filter, with a cutoff frequency of 0.03 Hz. The highest

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TABLE 1. Subject characteristics.

	Mean ± SD	Males	Females
Age (yr)	24.9 ± 6.6	23.8 ± 3.2	26.0 ± 8.9
Height (cm)	171.9 ± 10.6	180.7 ± 6.0	163.1 ± 5.4
Weight (kg)	66.8 ± 11.1	75.7 ± 6.9	57.8 ± 5.6
Fat (%)	16.4 ± 5.8	11.6 ± 2.4	21.2 ± 3.6
$\dot{V}O_{2max}$ (L·min^{-1})	3.66 ± 0.88	4.44 ± 0.39	2.87 ± 0.36

$\dot{V}O_{2max}$ data are from the 8-min protocol.

postprocessing value was defined as the $\dot{V}O_{2max}$. The presence of a $\dot{V}O_2$ plateau was assessed in the same software application, where the slope of the $\dot{V}O_2$–time relationship for the final 30 s was computed. $\dot{V}O_2$–time slope values < 0.05 L·min^{-1} were interpreted as a $\dot{V}O_2$ plateau (5). Also, individual $\dot{V}O_2$–time slope data, as described above, were used to assess the relationship between changes in the 30-s $\dot{V}O_2$–time slope across the protocol durations.

The ventilation threshold was assessed in the same software as for $\dot{V}O_{2max}$ and the $\dot{V}O_2$ plateau, where three regions of the $\dot{V}_E/\dot{V}O_2$–time curve were selected and linear regression segments were computer generated. The intersection of the lines represented thresholds, and the threshold coinciding with the most marked increase in $\dot{V}_E/\dot{V}O_2$ was used to detect the time at the ventilation threshold, as previously explained by Caiozzo (9). The computer program then linearly fit the $\dot{V}O_2$ curve and converted the time at the ventilation threshold to a $\dot{V}O_2$ value.

Testing protocols. The duration of each test to $\dot{V}O_{2max}$ was based on a computer-controlled ramp function to the cycle ergometer. On the basis of maximal power output from the familiarization trial (MPOF), ramp functions of 15–90 W·min^{-1} were used to determine protocol duration, as follows:

5-min protocol: MPOF (W)/5 (min) × 1.2
8-min protocol: MPOF (W)/8 (min) × 1.1
12-min protocol: MPOF (W)/12 (min) × 1.0
16-min protocol: MPOF (W)/16 (min) × 0.9

During the test, subjects were instructed to pedal at a self-selected cadence greater than 60 rpm, and to maintain this rate throughout the trial. The criterion for termination of the exercise tests was failure to maintain 40 rpm, or volitional fatigue and test termination.

Statistics. All data are presented as means ± standard deviation and were analyzed using Statistica (Statsoft, Version 5.1, Tulsa, OK). A two-way analysis of variance with repeated measures was used to examine differences across the various test protocols and between genders. When a significant F ratio was obtained, Tukey's *post hoc* test was used to locate significant differences between means. Relationships between variables were assessed using simple linear regression (Prism 3.0, GraphPad Software, San Diego, CA). The role of fitness in the $\dot{V}O_{2max}$ response to different protocol durations was assessed using analysis of covariance, with the highest $\dot{V}O_{2max}$ of each subject used as the covariate. The acceptable level of significance was set *a priori* at $P < 0.05$.

RESULTS

Descriptive characteristics of subjects. The descriptive characteristics of the subjects are presented in Table 1. The characteristics indicate that subjects varied with respect to fitness level, age, height, weight, and % body fat. Men and women were classified as above 80% of maximal aerobic power in their age group on the basis of cardiovascular fitness classification norms (2).

Effects of the four incremental tests on $\dot{V}O_{2max}$. The averages and ranges of test times for each protocol are shown in Table 2. All subjects performed the tests within 60 s of the goal time set for this investigation. There were significant differences in $\dot{V}O_{2max}$ across the four test protocols and between genders (Fig. 1A). $\dot{V}O_{2max}$ was higher in men than in women for all durations ($P < 0.001$). For women, no differences existed in $\dot{V}O_{2max}$ between any protocol durations. For men, $\dot{V}O_{2max}$ was significantly higher for the 8-min protocol compared with all other protocol durations ($P = 0.015$ for the 5-min protocol; $P < 0.001$ for the 12- and 16-min protocols). Figure 1B presents the $\dot{V}O_{2max}$ data for all test durations, expressed as a percentage of the highest $\dot{V}O_{2max}$. The numbers of subjects who attained their highest $\dot{V}O_{2max}$ for the 5-, 8-, 12-, and 16-min durations were zero, seven, one, and zero for men, and two, two, one, and three for women, respectively. The data were remarkably consistent for men, with 88% of subjects attaining their highest $\dot{V}O_{2max}$ at 8 min. In addition, the slope decrement in $\dot{V}O_{2max}$ with changes in duration was similar for shorter and longer protocols, at 1.3 and 1.0%·min^{-1} for comparisons of the 8-min versus the 5- and 16-min protocols, respectively. We do not have the data to comment on the extent of the linearity of these decrements.

In an effort to model the $\dot{V}O_{2max}$ response across different protocol durations, we combined our mean data (combined male and female data) with those of Astorino et al. (4) to increase the number of protocol-duration conditions from four to seven (Fig. 2). We then converted $\dot{V}O_{2max}$ data to % $\dot{V}O_{2max}$ and performed a fourth-order polynomial fit to the combined dataset, as well as a two-segment linear regression. Both models revealed a nadir close to 8 min and a negative $\dot{V}O_{2max}$ slope for longer times, at a rate of −0.731% $\dot{V}O_{2max}$ per minute. This amounts to a

TABLE 2. Average test time (min) for the four protocols.

	Mean ± SD	Males	Females
5 min	5.05 ± 0.17	5.12 ± 0.18	4.98 ± 0.13
8 min	7.77 ± 0.23	7.84 ± 0.20	7.69 ± 0.26
12 min	11.53 ± 0.42	11.49 ± 0.45	11.58 ± 0.40
16 min	16.25 ± 0.42	16.02 ± 0.37	16.49 ± 0.31

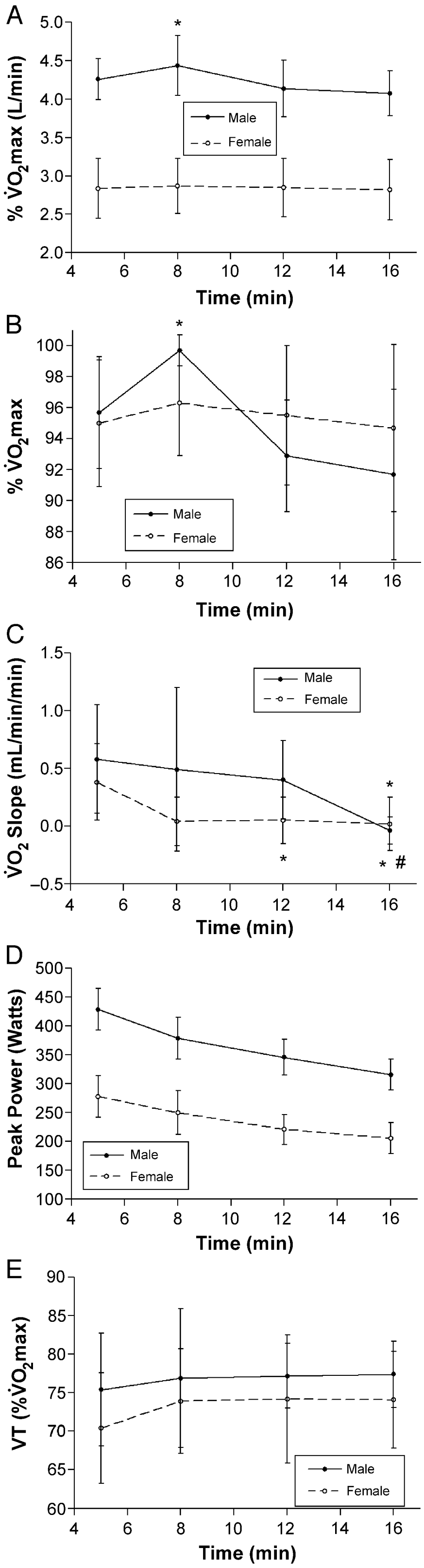

FIGURE 1—Stack plot (mean ± SD) for *A*) $\dot{V}O_{2max}$, *B*) % $\dot{V}O_{2max}$, *C*) $\dot{V}O_2$ slope for the last 30 s of the protocol, *D*) peak power at $\dot{V}O_{2max}$, and *E*) % $\dot{V}O_{2max}$ at the ventilation threshold. *A*) * Significantly different from 5, 12 and 16 min. *B*) # Significantly different from 5, 8, and 12 min; * significantly different from 5 min.

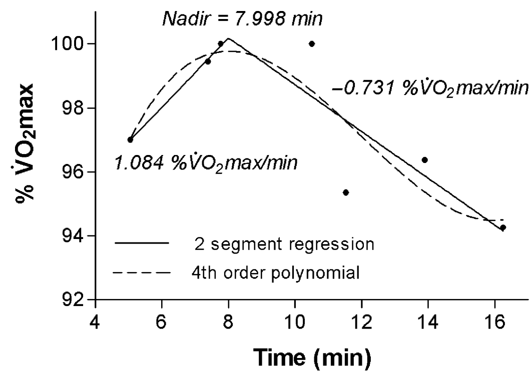

FIGURE 2—Compilation of the present (male and female) $\dot{V}O_{2max}$ data, expressed as % $\dot{V}O_{2max}$, combined with the data of Astorino et al. (4).

0.5-mL·kg^{-1}·min^{-1}·min^{-1} decrease for a $\dot{V}O_{2max}$ of 70 mL·kg^{-1}·min^{-1}. Interestingly, the slope function for shorter durations is only slightly different, at 1.084 % $\dot{V}O_{2max}$ per minute, equating to 0.76 mL·kg^{-1}·min^{-1}·min^{-1} for a $\dot{V}O_{2max}$ of 70 mL·kg^{-1}·min^{-1}. It is important to emphasize the similarity of the data from two different laboratories, $\dot{V}O_{2max}$ systems, different exercise modes (cycle ergometry and treadmill running), and subject samples.

Effects of the four incremental tests on incidence of $\dot{V}O_2$ plateau. The mean data for the $\dot{V}O_2$ slope is presented in Figure 1C. For men, the 5-min (P < 0.001) and 8-min (P = 0.017) protocols had a higher slope compared with the 16-min protocol. For women, the 12-min (P = 0.037) and 16-min (P = 0.012) protocols had a lower slope than the 5-min protocol. $\dot{V}O_2$–time slope values < 0.05 L·min^{-1} during the last 30 s of the test to $\dot{V}O_{2max}$ were interpreted as a $\dot{V}O_2$ plateau. For the 5-, 8-, 12-, and 16-min protocols, a $\dot{V}O_2$ plateau was found in one, three, two, and five male subjects and in one, six, four, and four female subjects.

In an effort to assess whether the $\dot{V}O_2$ slope was related to the fitness of the subject, we performed regression analyses between the $\dot{V}O_2$ slope and $\dot{V}O_{2max}$, expressed in milliliters per kilogram per minute. There was no significant relationship (P > 0.05) between $\dot{V}O_2$ slope and $\dot{V}O_{2max}$ in the subjects across all four durations.

Effects of the four incremental tests on power output and ventilation threshold. The average maximal power outputs across the four protocols and between genders were significantly (P < 0.001) different (Fig. 1D). All power-output *post hoc* mean comparisons were significantly different (P < 0.001), revealing that the higher $\dot{V}O_{2max}$ at 8 min for the men occurred at a significantly lower peak power than during the 5-min protocol (P < 0.001). In addition, the nonsignificant protocol-duration $\dot{V}O_{2max}$ findings for women occurred despite significant decreases in peak power as protocol duration increased (P < 0.001).

The mean and standard deviation values at ventilation threshold for the four protocols are presented in Figure 1E.

TABLE 3. $\dot{V}_{Emax}$, HR_{max}, maximal O_2 pulse, and $\dot{V}_E/\dot{V}O_{2max}$ (mean ± SD) in four protocols.

	5 min	8 min	12 min	16 min
$\dot{V}_{Emax}$ ($L \cdot min^{-1}$)				
Male	130.4 ± 19.8	136.2 ± 18.6	131.2 ± 15.5	130.0 ± 17.9
Female	81.7 ± 10.7	81.9 ± 12.1	82.1 ± 12.1	79.4 ± 10.3
HR_{max} (bpm)				
Male	181.4 ± 6.9	183.8 ± 6.5	185.1 ± 7.1	184.8 ± 8.7
Female	179.4 ± 11.9*	184.0 ± 12.9	184.0 ± 11.6	185.5 ± 10.9
Maximal O_2 pulse (milliliters per beat)				
Male	24.8 ± 3.2	25.5 ± 4.3	22.9 ± 2.0	23.0 ± 1.6
Female	15.9 ± 2.2	16.1 ± 2.4	16.2 ± 2.9	15.9 ± 3.3
$\dot{V}_E/\dot{V}O_{2max}$				
Male	35.2 ± 7.7	32.7 ± 3.7	32.7 ± 4.1	33.9 ± 3.7
Female	32.2 ± 2.3	35.2 ± 7.4	33.8 ± 6.0	31.3 ± 1.6

* Significantly lower compared with the 8-, 12-, and 16-min protocols.

The repeated-measures ANOVA did not detect a significant difference in mean $\dot{V}O_2$ at ventilation threshold across the four protocols or between genders. The mean values at ventilation threshold across the four protocols were detected at approximately 76% $\dot{V}O_{2max}$.

Effect of the four test protocols on $\dot{V}_{Emax}$, maximal heart rate, maximal O_2 pulse, and $\dot{V}_E/\dot{V}O_{2max}$. There were no significant differences in $\dot{V}_{Emax}$, maximal O_2 pulse, or $\dot{V}_E/\dot{V}O_{2max}$ across the four protocols. However, maximal heart rate was significantly different for female subjects between the 5-min protocol and all other durations ($P = 0.002$ for the 8-min protocol; $P < 0.001$ for the 12- and 16-min protocols) (Table 3). Table 4 presents the 95% confidence intervals for all variables.

DISCUSSION

Effect of protocol duration on $\dot{V}O_{2max}$. The primary purpose of this study was to compare $\dot{V}O_{2max}$, $\dot{V}O_2$–time slopes at the end of the protocol (last 30 s), and the presence of a $\dot{V}O_2$ plateau across four protocols of different durations (5, 8, 12, and 16 min) in men and women during incremental cycling exercise to $\dot{V}O_{2max}$. The major finding in this study was that shorter-duration $\dot{V}O_{2max}$ protocols (6–10 min) produce higher values for $\dot{V}O_{2max}$ for moderately to highly trained individuals on the cycle ergometer. Gender differences in the $\dot{V}O_{2max}$ responses were explained by fitness.

This finding is in contrast to those of Buchfuhrer et al. (7), who have demonstrated that 8- to 17-min tests elicited higher $\dot{V}O_{2max}$ values than tests that are shorter than 8 min on the treadmill and cycle ergometer. However, the Buchfuhrer et al. investigation was limited to a sample size of five subjects (mean age 36 ± 9.7 yr, mean $\dot{V}O_{2max}$ 52 ± 8.4 $mL \cdot kg^{-1} \cdot min^{-1}$) and, consequently, had low statistical power and a high likelihood for subject sampling bias, type II errors, and subsequently invalid results. This study, from a larger sample with varying age, gender, and fitness, shows that $\dot{V}O_{2max}$ in an 8-min protocol for male subjects was higher compared with protocol durations of 5, 12, and 16 min. The nonsignificant $\dot{V}O_{2max}$ data for women are original results, and the use of fitness (highest $\dot{V}O_{2max}$) as a covariate reveals that the issue of protocol duration was more important for moderately to highly endurance trained subjects.

The female subject data from the current study are in agreement with previous research (4,14,20,21). Fairshter et al. (14) compared a short-duration (15-s incremental exercise protocol = 5-min duration) to a long-duration (1-min incremental protocol = 15-min duration). During the incremental exercise tests, power output was incremented at a rate of 16.3 W per stage in both protocols. The $\dot{V}O_{2max}$ values of the two protocols were not significantly different. In addition, $\dot{V}_E$, O_2 pulse, and heart rate were not different between the two protocols. In the current study, $\dot{V}O_{2max}$, $\dot{V}_{Emax}$, and maximal O_2 pulse between the shortest (5 min) protocol and the longest (16 min) protocol were not different.

McCole et al. (21) and Lepretre et al. (20) also have shown no difference in $\dot{V}O_{2max}$ between shorter (6 min) and longer (12 min) protocols. McCole et al.'s study demonstrates that the duration of the treadmill protocols was not well controlled, in that the 6-min protocol ranged from 5.6 to 7.8 min and the 12-min protocol ranged from 9.4 to 15.4 min. Despite this limitation, the major finding of McCole et al. was that maximal cardiac output was significantly greater in the 6-min protocol than in the 12-min protocol. The greater maximal cardiac output was the direct result of a significantly greater stroke volume, because there were no significant differences in maximal heart rate between the 6- and 12-min protocols.

There are two possible explanations for the role of fitness, which explains the gender effect of our results, in the protocol-duration dependence of $\dot{V}O_{2max}$. The first explanation concerns the higher $\dot{V}O_2$–time slope of protocols

TABLE 4. Ninety-five-percent confidence intervals for male and female subjects' data.

	95% Confidence Intervals							
	5 min		8 min		12 min		16 min	
	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
$\dot{V}O_{2max}$ ($L \cdot min^{-1}$)								
Male	4.03	4.49	4.12	4.76	3.83	4.45	3.83	4.32
Female	2.51	3.14	2.57	3.17	2.53	3.17	2.82	3.15
% $\dot{V}O_{2max}$								
Male	92.7	98.7	98.7	100.5	89.9	95.9	87.1	96.3
Female	91.6	98.4	93.5	99.2	91.8	99.3	90.1	99.2
Power at $\dot{V}O_{2max}$ (W)								
Male	398	459	349	409	320	372	294	339
Female	248	308	218	281	200	243	184	229
$\dot{V}O_2$ slope								
Male	0.19	0.97	−0.11	1.08	0.11	0.69	−0.14	0.07
Female	0.11	0.66	−0.14	0.21	−0.12	0.22	−0.17	0.22
% $\dot{V}O_{2max}$ at VT								
Male	69.3	81.5	69.4	84.4	72.8	81.6	73.8	80.9
Female	69.3	81.4	68.2	79.5	67.2	81.1	68.8	79.4
$\dot{V}_{Emax}$ ($L \cdot min^{-1}$)								
Male	113.9	147.0	120.7	151.8	118.2	144.1	115.0	144.9
Female	72.8	90.7	71.8	92.0	92.0	92.2	70.4	88.0
HR_{max} (bpm)								
Male	175.6	187.1	178.4	189.1	179.2	191.0	177.5	192.0
Female	168.4	190.5	172.1	195.9	174.3	193.7	176.4	194.6
Maximal O_2 pulse (milliliters per beat)								
Male	22.2	27.4	21.9	29.0	21.2	24.6	21.7	24.4
Female	13.9	17.9	13.8	18.3	13.7	18.6	13.2	18.7
$\dot{V}_E/\dot{V}O_{2max}$								
Male	28.8	41.7	29.6	35.8	29.3	36.2	30.8	37.0
Female	30.2	34.2	29.0	41.4	28.9	38.9	30.0	32.7

for more fit individuals. These subjects need to generate and tolerate higher power outputs, and extending the time to $\dot{V}O_{2max}$ at these rates of power output may extend the duration of increasing nonmitochondrial metabolic contributions, thereby causing premature fatigue and test termination. The second factor may be attributable to limitations in central cardiovascular function. For example, McCole et al. (21) and Lepretre et al. (20) studied central cardiovascular responses during incremental exercise. The main findings were that maximal cardiac output seems to reach a peak when exercise protocol durations are between 5 and 9 min. The subjects of these investigations were all well trained (mean $\dot{V}O_{2max}$ = 50.7 $mL \cdot kg^{-1} \cdot min^{-1}$) and mostly male; as such, they closely resemble the male subjects of this study. The maximal cardiac output data, therefore, closely parallel our $\dot{V}O_{2max}$ changes for male subjects across the different protocol durations of this study. Presumably, the role of central cardiovascular function may be less important to $\dot{V}O_{2max}$ for less-fit individuals.

The present study's major finding for male subjects is similar to results found by Astorino et al. (4), who have shown that $\dot{V}O_{2max}$ was significantly higher in response to incremental protocol durations of approximately 7–10 min. Astorino et al. studied the effects of three different durations (approximately 7, 10, and 14 min) of incremental treadmill $\dot{V}O_{2max}$ tests with 26 healthy subjects (ages = 21 ± 3 yr). There was no difference in mean $\dot{V}O_{2max}$ between the 7-min protocol (3.56 ± 0.83 $L \cdot min^{-1}$) and the 10-min protocol (3.58 ± 0.83 $L \cdot min^{-1}$), yet $\dot{V}O_{2max}$ was significantly lower in the 14-min protocol (3.45 ± 0.79 $L \cdot min^{-1}$) than in the 7- and 10-min protocols. Astorino et al. suggest that the lower $\dot{V}O_{2max}$ in long-duration protocols (> 10 min) might be attributable to lower cardiac output, higher core temperature, and failure to reach the same maximal workload. This latter explanation was clearly supported by our data, where maximal power decreased significantly with increased test length (Fig. 1D). The combined datasets of Astorino et al. (4) and this study (Fig. 2) clearly reveal the superiority of the 8-min protocol duration for either cycle ergometry or treadmill running in subjects with moderate to high cardiorespiratory fitness.

Presence of a $\dot{V}O_2$ plateau. The presence of a $\dot{V}O_2$ plateau in this study was achieved in 12.5, 37.5, 25, and 62.5% of men for each of the 5-, 8-, 12-, and 16-min protocols, respectively. For women, the data were 12.5, 75, 50, and 50%, respectively. The current investigation assessed the presence of a plateau by using the slope of the $\dot{V}O_2$–time relationship in the final 30 s of the test. $\dot{V}O_2$–time slope values < 0.05 $L \cdot min^{-1}$ were interpreted as a $\dot{V}O_2$ plateau.

Since Hill and Lupton (16) introduced the concept of a $\dot{V}O_2$ plateau in the early 1920s, no suitable criteria to determine a plateau have existed for more than 82 yr. Previous studies have shown that the incidence of a $\dot{V}O_2$ plateau ranged from 33 to 94% of subjects tested, depending on plateau criterion used, test protocol, and subjects (12,13,22). In the present study, no subject achieved a $\dot{V}O_2$ plateau in all four protocols. In addition, there was no specific pattern to show that longer protocols had a higher incidence of a $\dot{V}O_2$ plateau than protocols as short as 8 min (Table 4).

Interestingly, in this study, the mean $\dot{V}O_2$–time slope for long-duration protocols (> 12 min) was lower than the mean $\dot{V}O_2$–time slope for short-duration protocols (< 8 min), yet short-duration protocols elicited higher $\dot{V}O_{2max}$ values. This may be explained by the time frame we used (final 30 s) for detecting a $\dot{V}O_2$ plateau. The final 30-s duration may be too long to use as a criterion to detect a plateau in the short-duration protocols, because there may be too large an increase in workload/time to adequately detect a plateau. In addition, subjects may not be able to sustain high-intensity incremental exercise for long enough to exhibit a plateau in $\dot{V}O_2$, no matter what their level of training.

Another explanation may be the result of the relationship between $\dot{V}O_2$–time slope and $\dot{V}O_{2max}$. The present study data show that $\dot{V}O_2$–time slope versus $\dot{V}O_{2max}$ across the four protocols had no significant relationship. A recent study has shown similar results: Astorino and colleagues (5) show that there was no correlation between $\dot{V}O_{2max}$ and $\Delta\dot{V}O_2$ at $\dot{V}O_{2max}$. To date, no published papers have shown protocols of different duration to affect the incidence of plateau during a $\dot{V}O_{2max}$ test. Future investigations are needed to study whether protocol duration affects the presence of a $\dot{V}O_2$ plateau at $\dot{V}O_{2max}$ in subjects of different fitness and/or health status.

It is tempting to speculate that the $\dot{V}O_2$ plateau may be less important in defining $\dot{V}O_{2max}$ than previously thought, because we have shown higher $\dot{V}O_{2max}$ data for the 8-min protocol for the men when the $\dot{V}O_2$–time slope was higher than for the longer protocols. However, care should be taken here, because the short protocols had a higher $\dot{V}O_2$–time slope across the protocol, and, by definition, they also provided less time for subjects to exercise close to $\dot{V}O_{2max}$ and establish a $\dot{V}O_2$ plateau. Our $\dot{V}O_2$–time slope data may have changed if we started our subjects at a higher initial power and kept a similar $\dot{V}O_2$–time slope between protocols. Until this is done and compared in research, it is difficult to interpret our data regarding the incidence of a $\dot{V}O_2$ plateau and the $\dot{V}O_2$–time slope.

Despite the differences in $\dot{V}O_2$ slope and $\dot{V}O_{2max}$ between the protocols, $\dot{V}_{Emax}$, maximal O_2 pulse, and $\dot{V}_E/\dot{V}O_{2max}$ were not different across the four protocols. These data indirectly support a noncardiopulmonary limitation to $\dot{V}O_{2max}$ and the presence of the $\dot{V}O_{2max}$ plateau. Future investigations are needed to determine whether cardiopulmonary function is limited during a $\dot{V}O_{2max}$ test.

Ventilation threshold findings. Many studies have examined the ventilation threshold in highly trained subjects (1,17,19,24). In the present study, the mean ventilation threshold value was detected at approximately 76% of $\dot{V}O_{2max}$ across the four protocols in both men and women. Previous studies by Albrecht et al. (1) and Kreider (19) have reported that ventilation threshold values among triathletes were 78.8 and 85% of $\dot{V}O_{2max}$, respectively.

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Schneider et al. (24) have shown ventilation threshold values to be 65.3% of $\dot{V}O_{2max}$ in 10 male triathletes, whereas Hue et al. (17) have shown ventilation threshold to be 66.8% of $\dot{V}O_{2max}$ in 29 male triathletes. The important applied result of this investigation is that protocol duration does not affect ventilation threshold. This finding is important because it shows that there is no loss in sensitivity or accuracy for detecting the ventilation threshold from a short-duration protocol. Thus, the ventilation threshold can still be obtained from short protocols, allowing just one test to measure ventilation threshold and $\dot{V}O_{2max}$.

CONCLUSIONS AND RECOMMENDATIONS

The purpose of this investigation was to compare $\dot{V}O_{2max}$ and the presence of a $\dot{V}O_2$ plateau across four protocol durations during incremental cycling exercise to $\dot{V}O_{2max}$ in men and women. We assessed the role of fitness in the $\dot{V}O_{2max}$ response to different protocol durations by using the highest subject $\dot{V}O_{2max}$ as a covariate. Because removing fitness (highest $\dot{V}O_{2max}$ covariate) removed all protocol-duration differences in $\dot{V}O_{2max}$, the $\dot{V}O_{2max}$ response to protocol duration is dependent on the fitness of the subjects. Subjects with moderate to high cardiorespiratory fitness (i.e., most of the men of this study) require a protocol duration of 8 min to maximize the peak $\dot{V}O_2$ attained during incremental exercise. The protocol duration used in incremental exercise is less influential regarding $\dot{V}O_{2max}$ measurement in less-fit individuals. Nevertheless, because the female data reveal that $\dot{V}O_{2max}$ values were not different for any different durations, we feel that when testing young, healthy, active individuals, the protocol duration for $\dot{V}O_{2max}$ assessment should be between 8 and 10 min (Fig. 2). Protocol durations in excess of 12 min are likely to induce a low $\dot{V}O_{2max}$ measurement. The field of exercise physiology is still in need of objective criteria to ascertain the attainment of a true $\dot{V}O_{2max}$ and the establishment of a $\dot{V}O_2$ plateau.

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