ORIGINAL RESEARCH ARTICLE

Maintenance of hyperglycaemia does not improve performance in a 100 km cycling time trial

Andrew N Bosch (PhD)
Mark C Kirkman (BSc (Med)(Hon) Exercise Science)
UCT/MRC Research Unit for Exercise Science and Sports Medicine, Nelwands, Cape Town

Abstract

Objectives. The aim of this study was to determine whether the elevated plasma glucose oxidation rate (~ 1.8 g.min^{-1}) in the latter stages of prolonged exercise in subjects in which hyperglycaemia (± 10 mmol.l^{-1}) is maintained via a glucose clamp, improves 100 km cycling time-trial (TT) performance.

Design. Seven endurance-trained male cyclists (22±4 yrs) participated in this randomised crossover trial. On two occasions, separated by 7 - 10 days, subjects performed a self-paced TT in the laboratory. During one TT blood glucose was maintained at a euglycaemic concentration of ± 5 mmol.l^{-1} (ETT) and during the other, at ±10 mmol.l^{-1} (HTT). Each TT was interspersed with 5 X 1 km high-intensity periods (HIP) and 4 X 4 km HIP, in an attempt to mimic the variable intensity of competitive road races. Subjects were instructed to complete the TT in the 'fastest time possible', taking the 9 HIP (21 km) into consideration.

Results. There were no significant differences between ETT and HTT in overall time (143:09±7:14 v. 142:23±7:16 min:s), mean power (275±39 v. 279±39 W) and heart rate (160±9 v. 158±11 beats.min^{-1}).

Conclusion. Time trial performance over 100 km is not improved by maintaining a hyperglycaemic (10 mmol.l^{-1}) blood glucose concentration.

Introduction

Carbohydrate (CHO) ingestion and the maintenance of euglycaemic blood glucose concentration have long been known to improve performance during prolonged exercise (> 90 min duration) [12, 15, 22.] However, it was not until the 1980s that the performance benefits of CHO ingestion during prolonged exercise were finally resolved.

It has been shown by many studies that cycling endurance performance is enhanced when CHO is ingested during prolonged exercise. [4-9] There are two mechanisms that were originally proposed to explain these findings. The first suggests that there is a muscle glycogen-sparing effect.[1, 9,16] However, this mechanism has been refuted by a number of studies, including those of Bosch *et al.*,[2] Coyle *et al.*,[8] Flynn *et al.*[13] and Levine *et al.*[21] The second and more widely accepted mechanism is that CHO feeding delays the onset of fatigue by maintaining blood glucose concentrations and thereby preventing hypoglycaemia, via a liver glycogen-sparing effect.[2,3]

The maximum rate of ingested CHO oxidation that can be achieved during the later stages of prolonged exercise is approximately 1 g.minute^{-1} (for review see[19]). Hawley *et al.*[18] reported a similar upper limit to exogenous CHO oxidation (1.1 ± 0.1 g.min^{-1}) after 120 minutes of exercise, when glucose was infused to maintain euglycaemia. In the same study it was shown that under conditions of hyperglycaemia (~10 mmol.l^{-1}), the plasma glucose oxidation increased to ~ 1.8 g.min^{-1} during the final 30 minutes of exercise. This is in agreement with the suggestion by Coyle *et al.*[10] that oxidation rates of exogenous CHO may be able to reach 2 g per minute under hyperglycaemic conditions.

These studies, as well as the performance studies described previously, were all carried out at constant workloads (70-75% of $V0_{2max}$). Typically, during competitive road cycling races the workload is not constant but varies, depending on the terrain, course profile, environmental conditions and the racing strategies of the cycling group.[24] It is also important to note that none of the studies on the oxidation rate during hyperglycaemia investigated the possible associated effects on cycling performance. Hawley *et al.*,[17] however, have suggested that hyperinsulinaemia associated with hyperglycaemia may have an adverse effect on endurance performance during the first 90 - 120 minutes of prolonged exhaustive exercise.

Thus, the aim of the current study was to investigate any possible ergogenic effect of maintained hyperglycaemia on performance during a 100 km cycling laboratory time trial (TT) that was designed to simulate the variable intensity of competitive road racing.

CORRESPONDENCE:

A N Bosch
UCT/MRC Research Unit for Exercise Science and Sports Medicine
Department of Human Biology
University of Cape Town
PO Box 115
Newlands 7725
Tel: 021-650-4578
Fax: 021-686-7530
E-mail: Andrew.Bosch@uct.ac.za

Methods

Subjects

Seven endurance-trained male cyclists participated in the study, which was approved by the Research Ethics Committee of the Faculty of Health Sciences of the University of Cape Town. All cyclists were training between 200 and 400 km per week and had completed a 105 km road race in less than 3 hours. Subject characteristics are shown in Table I. Prior to the start of the trial all subjects were informed of the purpose of the investigation, and since glucose was infused intravenously and blood samples were taken, the procedures and risks involved were explained to the subjects and their written informed consent was obtained.

Preliminary testing

On their first visit to the laboratory, subjects were tested for predicted peak oxygen uptake ($V0_{2peak}$) and peak power output (PPO) on their own bicycles, which were mounted on a Kingcycle ergometer (Kingcycle Ltd, High Wycombe, UK). The bicycle is attached to the ergometry system by the front fork and supported under the bottom bracket by an adjustable pillar. The bottom bracket support is used to adjust the rolling resistance of the rear wheel on an air-braked flywheel and the system is calibrated as previously reported by Palmer *et al.*[25] After a 5-10 min self-paced warm up, the test began at a workload of 200 W, which was increased by 20 $W.min^{-1}$ until volitional exhaustion. During each incremental test to exhaustion, subjects were instructed to remain in a seated position. PPO was taken as the highest average power during any 60 s period of the test. The ergometry system software predicted $V0_{2peak}$ from the PPO.

On their second visit to the laboratory, subjects performed a familiarisation ride. This ride was a TT identical to that which would be ridden during the experimental trials (described below), except that there was no intervention of any sort.

Experimental trials

Each subject completed a single blinded randomised cross-over design of two experimental TTs separated by 7-10 days. TTs were performed at the same time of the day under standard laboratory conditions (~22°C and 55% relative humidity). A large electric fan was used to cool the subjects during exercise. Subjects were requested to perform the same type of training for the duration of the trial and to refrain from heavy physical exercise on the day before each trial. They were also instructed to follow their normal diet for the 3 days leading up to each TT. The food consumed prior to the first TT was repeated prior to the next. They were required to keep training diaries and dietary records to assess their compliance to these conditions.

On the morning of each TT subjects reported to the laboratory between 07h00 and 08h00, 12-14 hours after an overnight fast. At this time their bicycle was mounted on the Kingcycle ergometer and the system was calibrated as previously described. A flexible 20-gauge Teflon cannula (Jelco; Johnson and Johnson, Halfway House, Gauteng, SA) attached to a three-way stopcock was positioned in an antecubital vein of the right forearm. This cannula was used for the variable-rate glucose (20% dextrose) infusion used to maintain blood glucose concentration at the predetermined value of either 5 $mmol.l^{-1}$ (ETT) or 10 $mmol.l^{-1}$ (HTT) for the duration of the TT. A flexible 18-gauge Teflon cannula attached to a three-way stopcock was positioned in an antecubital vein of the left forearm for blood sampling during the TTs. Blood samples (~ 0.5 ml) were drawn at 5 min intervals to measure blood glucose concentrations, so that glucose infusion rates could be adjusted via the glucose clamp technique[11] and modified for use during exercise by the authors to maintain the desired blood glucose concentration. A pocket gluco-meter (Accutrend; Boehringer Mannheim, Mannheim, Germany) was used to measure blood glucose concentration. The accuracy of the glucometer has previously been verified by comparison with a Beckman glucose analyser (Glucose analyser 2; Beckman Instruments, Fullerton, CA). Subjects were then connected to the infusion pump (Accura TG 2000, Trigate Ltd., Randburg, SA) used to infuse the 20% dextrose solution, mounted their bicycle and began a 5-10 min self-paced warm up. Just prior to the completion of the warm up, an initial priming dose of glucose was infused to achieve the desired blood glucose concentration for that TT (i.e. 5 or 10 $mmol.l^{-1}$).

TABLE I. Subject characteristics

Subject	Age (yr)	Height (m)	Mass (kg)	VO_{2peak} ($ml{\cdot}kg^{-1}\ min^{-1}$)	Peak power output (W)	P:W ($W\ kg^{-1}$)	HR_{peak} ($beats\ min^{-1}$)
1	21	1.84	64.0	81.3	466	7.28	196
2	26	1.86	89.5	58.4	468	5.23	186
3	21	1.85	73.5	61.6	404	5.50	180
4	19	1.78	83.0	56.6	420	5.06	193
5	17	1.67	58.0	76.9	398	6.86	194
6	28	1.73	72.0	61.6	396	5.50	191
7	22	1.68	65.0	65.2	378	5.82	186
Mean (SD)	22 (4)	1.77 (0.08)	72.1 (11.1)	65.9 (9.5)	419 (35)	5.89 (0.85)	189 (6)

VO_{2peak} = protected peak oxygen uptake; P:W = power to weight ratio; HR_{peak} = peak heart rate.

Following the warm up, subjects began the TT. In an attempt to mimic the changes in intensity associated with most competitive cycling road races, the TT included a series of high-intensity periods (HIP): 5 bouts of 1 km duration after 10, 32, 52, 72 and 99 km, as well as 4 bouts of 4 km HIP after 20, 40, 60 and 80 km. This protocol has previously been shown to be a repeatable measurement of performance (within-cyclist coefficient of variation of 1.7%).[26] Subjects were instructed to complete the TT in 'the fastest possible time', taking into consideration the HIP that were included in the protocol. Prior to the start of a HIP, an investigator gave a distance count down and instructed the cyclist to complete the HIP in the fastest possible time. A financial reward was offered to the subject who completed the entire trial and the HIP combined in the fastest time. In addition, verbal encouragement was also given during HIP in a further attempt to evoke a maximal effort. Prior to and during the ride, subjects viewed a diagram of the 'course profile', which graphically illustrated where each of the HIP occurred. Instantaneous power output was recorded at 500 m intervals during HIP to provide an estimate of average power output. Throughout each trial, power output, speed and elapsed time were monitored continuously and stored on computer. Heart rate (HR) was recorded using a Polar SportTester HR monitor (Polar Electro, Kempele, Finland). The only feedback the subjects received during the TT was elapsed distance and HR. During each TT, subjects were permitted to ingest water *ad libitum.*

Statistical analyses

All results are presented as means ± SD. Statistical significance ($p < 0.05$) of between group differences was assessed by a two-way analysis of variance (ANOVA) with repeated measures over time (Statistica for Windows, Version 6, Statsoft, Tulsa, OK, USA), followed by a Tukey's honest significant difference *post-hoc* test.

Results

Training and dietary diaries collected on the morning of each trial confirmed that each subject had followed a similar pre-trial routine for both trials. None of the subjects participated in high-intensity or long-duration exercise on the day before any of the trials. Mean blood glucose concentrations maintained during the trials by the glucose clamp were 4.9±0.2 mmol.l^{-1} and 10.1±0.3 mmol.l^{-1} for ETT and HTT, respectively.

The mean time, power output and heart rate for ETT and HTT were similar (Table II). There was also no significant time by group interaction effects between the trials with regards to time taken or mean power for the HIP (1 and 4 km) over the course of each TT.

The subjects became fatigued during the trial as the fourth l km HIP for both trials was significantly slower (p=0.016) compared with the first (Fig. 1A) and had a significantly lower mean power (p=0.004) compared with the first and the last HIP (p=0.02) (Fig. 1B). The mean power of the third 1 km HIP was also significantly lower (p=0.02) than the first in both trials (Fig. 1B). The second, third and fourth 4 km HIP (for both trials), were significantly slower (p=0.03, p=0.02 and p=0.01 respectively) compared with the first (Fig. 2 A). The mean power of the fourth 4 km HIP was significantly lower (p=0.01) compared with the first (Fig. 2B).

TABLE II. Mean time, power output and heart rate for ETT and HTT (*N*=7).

	ETT	HTT
Mean time (min:s)	143:09±7:14	142:23±7:16
Mean power output (W)	275±39	279±39
Mean heart rate (beats·min^{-1})	160±9	158±11

Values are mean ± SD.

Discussion

The most important finding was that the maintenance of hyperglycaemia had no significant effect on cycling performance during a prolonged (~140 min) self-paced TT, compared with euglycaemic control subjects. This finding is surprising, since glucose oxidation rates have been shown to reach ~1.8 g.min^{-1} during the last 20 minutes of an intense (~70 % of $V0_{2max}$) 2 hour cycle bout when hyperglycaemia is

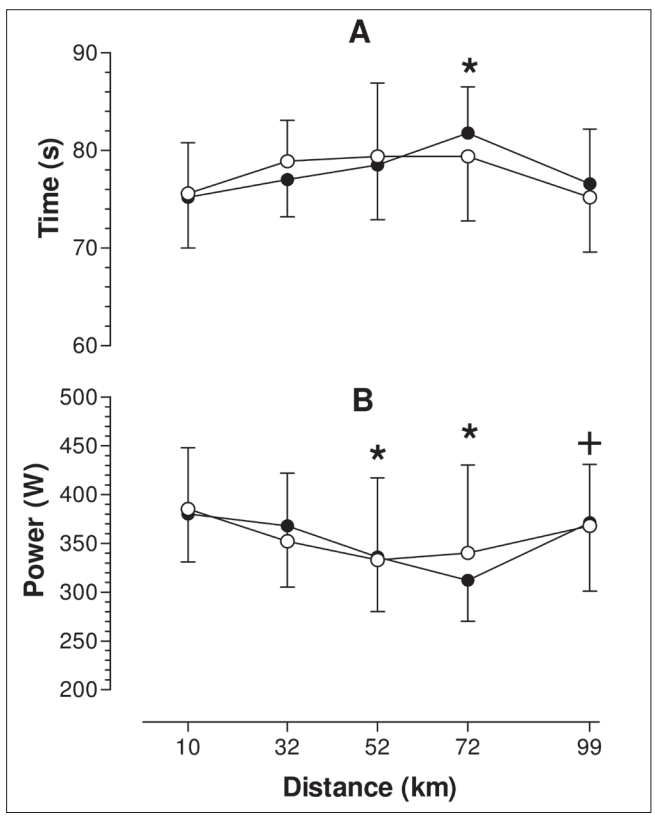

Fig. 1. (A) Time taken (seconds), and (B) average power (Watts) for the 1 km HIP during ETT (•) and HTT (o). * Denotes a significant difference (p<0.05) from the first HIP during ETT and HTT. + Denotes a significant difference (p<0.05) from the fourth HIP during ETT and HTT.

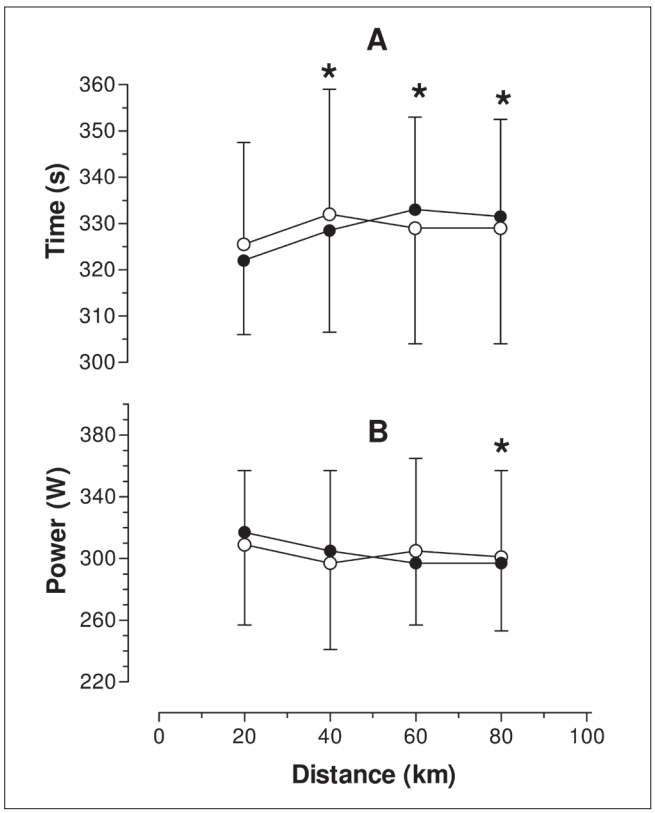

Fig. 2. (A) Time taken (seconds), and (B) average power (Watts) for the 4 km HIP during ETT (•) and HTT (o). * Denotes a significant difference (p<0.05) from the first HIP during ETT and HTT.

maintained[18] compared with 1.1 g.min^{-1} when euglycaemia is maintained via intravenous infusion of glucose. The higher oxidation rate suggests an improved supply of oxidative substrate to the exercising muscle, and therefore could result in an improved performance.

Endogenous liver glucose turnover is completely suppressed and fat oxidation is inhibited under these hyperglycaemic conditions, when initial muscle glycogen levels are normal (~130 mmol.kg^{-1} wet wt)[18] it can be assumed that subjects in this trial would have had similar, normal muscle glycogen concentrations at the start of each TT as they followed their normal diet for 3 days prior to each trial, and had not taken part in any heavy physical activity for at least 1 day prior to each TT. This is an important consideration as Weltan *et al.*[28,29] have demonstrated that whole-body metabolism responses are different when initial muscle glycogen levels are low (~ 80 mmol.kg^{-1} wet wt). Under these circumstances, muscle glycogen utilisation is reduced and fat oxidation rates are elevated. However, glucose oxidation rates are unaffected by initial muscle glycogen levels when either hyperglycaemia or euglycaemia was maintained via intravenous infusion of glucose.[28,29] Thus, in the current study, it is unlikely that differences in muscle glycogen concentration at the start of the TT would have had any influence on the rate of oxidation of the infused glucose.

The studies of Weltan *et al.*[28,29] indicate that the percentage contribution of each fuel substrate (i.e. muscle glycogen, plasma glucose and fat) to overall energy expenditure appears to be regulated in part by substrate availability at the start of exercise and Palmer *et al.*[23] have shown that overall energy expenditure is similar for work bouts of the same average intensity. Since exercise intensity in the current study was similar, with no significant difference between overall mean power for ETT and HTT (275±39 W v. 279±39 W), this suggests a similar overall energy expenditure for ETT and HTT. The results of this study therefore indicate that the substrate that is predominantly utilised during exercise lasting between 2 and 3 hours, has no effect on performance. This is in contrast to suggestions by Gisolfi and Duchman[14] and Hawley *et al.*,[17] that the inhibition of fat oxidation in the early part of exhaustive endurance events may be detrimental to performance.

Pacing data from this study appear to support the concept of teleoanticipation during closed loop exercise bouts. Teleoanticipation is the process whereby performance is regulated by central calculations and efferent commands in an attempt to couple the metabolic and biomechanical limits of the body to the demands of the exercise task at hand.[27] The time and power for the last 1 km HIP was not significantly different from the first HIP (Fig. 1), although the fourth HIP was significantly slower. This ability to complete the last HIP at a similar pace to the first is not surprising, as it has been observed previously.[20] It must also be remembered that most cycle road races end with a bunch sprint for the finish and as a result competitive cyclists would be prepared for this.

It is interesting to speculate that the progressive decrement in performance from the first to the fourth HIP in the l km HIP, and the 4 km HIP (Figs 1 and 2), may be the result of afferent feedback after the first HIP resetting the subconscious efferent command in order to maintain a reserve to complete the entire TT. As subjects in this study were given a financial incentive and vociferous verbal encouragement in order to complete each HIP in the fastest time possible, it may be assumed that their conscious effort was the same during all HIPs. Therefore, we suggest that a subconscious down-regulation of power output via efferent command may be responsible for the decrease in performance during the HIP, prior to the last 1 km HIP. Although efferent command was not measured during this study, this has been shown to occur by Kay *et al.*[20]

In conclusion, the results of the current study show that in well-trained cyclists, hyperglycaemia (i.e. a plasma glucose concentration of ~ 10 mmol.l^{-1}) does not improve cycling TT performance.

References

1. Bergstrom J, Hultman E. A study of the glycogen metabolism during exercise in man. *Scand J Clin Lab Invest* 1967; 19: 218-28.
2. Bosch AN, Dennis SC, Noakes TD. Influence of carbohydrate ingestion on fuel substrate turnover and oxidation during prolonged exercise. *J Appl Physio*l 1994; 76: 2364-72.
3. Bosch AN, Weltan SM, Dennis SC, Noakes TD. Fuel substrate kinetics of carbohydrate loading differs from that of carbohydrate ingestion during prolonged exercise. *Metabolism* 1996; 45: 415-23.
4. Brooke JD, Davies GJ, Green LF. The effects of normal and glucose syrup work diets on the performance of racing cyclists. *J Sports Med* 1975; 15: 257-65.
5. Coggan AR, Coyle EF. Effect of carbohydrate feedings during high-intensity exercise. *J Appl Physiol* 1988; 65: 1703-09.
6. Coggan AR, Coyle EF. Metabolism and performance following carbohydrate ingestion late in exercise. *Med Sci Sports Exerc* 1989; 21: 59-65.
7. Coggan AR, Coyle EF. Reversal of fatigue during prolonged exercise by carbohydrate infusion or ingestion. *J Appl Physiol* 1987; 63: 2388-95.
8. Coyle EF, Coggan AR, Hemmert MK, Ivy JL. Muscle glycogen utilization during prolonged strenuous exercise when fed carbohydrate. *J Appl Physiol* 1986; 61: 165-72.
9. Coyle EF, Hagberg JM, Hurley BF, Martin WH, Ehsani AA, Holloszy JO. Carbohydrate feeding during prolonged strenuous exercise can delay fatigue. *J Appl Physiol* 1983; 55: 230-5.
10. Coyle EF, Hamilton MT, Alonso IG, Montain SJ, Ivy JL. Carbohydrate metabolism during intense exercise when hyperglycemic. *J Appl Physiol* 1991; 70: 834-40.
11. Defronzo RA, Tobin JD, Andres R. Glucose clamp technique: a method for quantifying insulin secretion and resistance. *Am J Physiol* 1979; 237 (*Endocrinol Metab Gastrointest Physiol* 6): E214-E233.
12. Dill DB, Edwards HT, Talbott JH. Studies in muscular activity. VII. Factors limiting the capacity for work. *J Physiol* (*Lond*) 1932; 77: 49-62.
13. Flynn MG, Costill DL, Hawley JA, *et al.* Influence of selected carbohydrate drinks on cycling performance and glycogen use. *Med Sci Sports Exerc* 1987; 19: 37-40.
14. Gisolfi CV, Duchman SM. Guidelines for optimal replacement beverages for different athletic events. *Med Sci Sports Exerc* 1992; 24: 679-87.
15. Gordon B, Kohn LA, Levine SA, Matton M, Schriver W, Whiting WB. Sugar content of the blood in runners following a marathon race. With especial reference to the prevention of hypoglycemia: further observations. *JAMA* 1925; 85: 508-9.
16. Hargreaves MD, Costill DL, Coggan AR, Fink WI, Nishibata I. Effect of carbohydrate feedings on muscle glycogen utilization and exercise performance. *Med Sci Sports Exerc* 1984; 16: 219-22.
17. Hawley JA, Bosch AN, Weltan SM, Dennis SC, Noakes TD. Effects of glucose ingestion or glucose infusion on fuel substrate kinetics during prolonged exercise. *Eur J Appl Physiol* 1994; 68: 381-9.
18. Hawley JA, Bosch AN, Weltan SM, Dennis SC, Noakes TD. Glucose kinetics during prolonged exercise in euglycemic and hyperglycemic subjects. *Pflugers Arch* 1994; 426: 378-86.
19. Hawley JA, Dennis SC, Noakes TD. Oxidation of carbohydrate ingested during prolonged endurance exercise. *Sports Med* 1992; 14: 27-42.
20. Kay D, Marino FE, Cannon J, St Clair Gibson A, Lambert MI, Noakes TD. Evidence for neuromuscular fatigue during high-intensity cycling in warm, humid conditions. *Eur J Appl Physiol* 2001; 84: 115-21.
21. Levine LW, Evans J, Cadarette BS, Fisher EC, Bullen BA. Fructose and glucose ingestion and muscle glycogen use during submaximal exercise. *J Appl Physiol* 1983; 55: 1767-71.
22. Levine SA, Gordon B, Derick CL. Some changes in the chemical constituents of the blood following a marathon race. With special reference to the development of hypoglycemia. *JAMA* 1924; 82: 1778-79.
23. Palmer GS, Borghouts LB, Noakes TD, Hawley JA. Metabolic and performance responses to constant-load vs. variableload exercise in trained cyclists. *J Appl Physiol* 1999; 87: 1186-96.
24. Palmer GS, Hawley JA, Dennis SC, Noakes TD. Heart rate responses during a 4-d cycle stage race. *Med Sci Sports Exerc* 1994; 26: 1278-83.
25. Palmer GS, Dennis SC, Noakes TD, Hawley JA. Assessment of the reproducibility of performance testing on an air-braked cycle ergometer. *Int J Sports Med* 1996; 17: 293-8.
26. Schabort EJ, Hawley JA, Hopkins WG, Mujika I, Noakes TD. A new reliable laboratory test of endurance performance for road cyclists. *Med Sci Sports Exerc* 1998; 30: 1744-50.
27. Ulmer HV. Concept of an extracellular regulation of muscular metabolic rate during heavy exercise in humans psychophysiological feedback. *Experientia* 1996; 52: 416-20.
28. Weltan SM, Bosch AN, Dennis SC, Noakes TD. Influence of muscle glycogen content on metabolic regulation. *Am J Physiol* 1998; 274 (*Endocrinol Metab* 37): E72-E82.
29. Weltan SM, Bosch AN, Dennis SC, Noakes TD. Pre-exercise muscle glycogen content affects metabolism during exercise despite maintenance of hyperglycemia. *Am J Physiol* 1998; 274 (*Endocrinol Metab* 37): E83-E88.