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GLYCEROL HYPERHYDRATION, ENDURANCE PERFORMANCE, AND CARDIOVASCULAR AND THERMOREGULATORY RESPONSES: A CASE STUDY OF A HIGHLY TRAINED TRIATHLETE

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ABSTRACT

GLYCEROL HYPERHYDRATION, ENDURANCE PERFORMANCE, AND CARDIOVASCULAR AND THERMOREGULATORY RESPONSES: A CASE STUDY OF A HIGHLY TRAINED TRIATHLETE. **Eric Goulet, Pierre Gauthier, Susan Labrecque, And Donald Royer. JEPonline**. 2002;5(2):19-28. This case study observed the effect of glycerol hyperhydration (GH) in a highly trained male triathlete on endurance performance and cardiovascular and thermoregulatory responses. For this purpose, the subject ingested, in a double-blind random fashion, either a glycerol solution (1.2 g/kg body weight [BW] with 26 mL/kg BW of fluid) or a placebo (26 mL/kg BW of fluid). The subject then performed 2 hr of cycling at 65% VO_2max and 25 °C, which was followed by an endurance performance test to exhaustion. During exercise, the subject drank 830 mL of sports drink. Compared to placebo hyperhydration (PH), GH increased total body water (TBW) by 1,033 mL before exercise. After 2 hr of cycling, sweat rate, heart rate and perceived exertion were similar between trials, but GH reduced urine production by 300 mL, prevented hypohydration, and decreased rectal temperature by 0.42 °C. Compared to PH, GH increased endurance performance by 24%, which was associated with a reduced rectal temperature of the order of 0.3 °C. Thus, in this highly trained triathlete, GH better maintained hydration during a 2 hr cycling exercise at 65% VO_2max, which reduced core temperature and improved endurance performance.

Key Words: Dehydration, Nutritional Ergogenic Aid, Prolonged Exercise, Rectal Temperature, Thermoneutral Climate, Total Body Water

INTRODUCTION

Comparatively to the ingestion of little (≤50% of sweat rate) or no fluid during prolonged moderate-intensity exercise, the ingestion of fluid at a rate that closely matches sweat rate has been shown to decrease core temperature (1-3) and heart rate (1-3), even in warm and thermoneutral climates. Of practical significance is that it has been shown, in a warm climate, that dehydration as low as 1.8% of BW impairs performance during a high-intensity (~85% VO_2max) cycling time trial (4) and decreases cycling time to exhaustion at 90% VO_2 peak (5).

During exercise, sweat rates in 20-32 °C environments can equal or exceed 1 L/hr (2-4) when, paradoxically, the rates of fluid intake of most endurance athletes in such circumstance are seldom more than 500 ml/hr (6). Consequently, because sweat rates are higher than fluid consumption, athletes develop dehydration during prolonged exercise. Hence, any hydration strategies whose goal would be to attenuate, delay or even eliminate the effect of dehydration during exercise should be given serious consideration. One such strategy is water hyperhydration before exercise. In fact, compared to beginning an exercise euhydrated, water hyperhydration has been reported to reduce core temperature (7,8) and heart rate (8,9) during a subsequent bout of exercise in which no fluid was provided. Likewise, Moroff and Bass (10) have demonstrated that, compared to pre-exercise euhydration with rehydration (1,200 mL) during a 90 min walk in the heat, water hyperhydration with rehydration increased sweat rate, and decreased rectal temperature and heart rate.

However, the efficacy of water hyperhydration in increasing TBW is limited because the kidneys are extremely efficient at rapidly getting rid of any fluid ingested in excess. One method to delay urine excretion and, hence, to prolong the state of hyperhydration, is to add glycerol to the fluid ingested during hyperhydration. Indeed, comparatively to PH, GH has been demonstrated to enhance TBW by an additional 250-660 mL (11-16) after 2-2.5 hr when 21-26 ml/kg BW of fluid with 0.9-1.5 g glycerol/kg BW have been ingested together. Hence, comparatively to PH, GH has been shown during exercise to reduce heart rate (15) and rectal temperature (13), increase sweat rate (13), and improve exercise capacity (12,15).

To our knowledge, no study has examined the effect of GH in highly trained athletes during a prolonged cycling exercise that is conducted in a thermoneutral climate (25 °C), and which is immediately followed by an endurance performance test to exhaustion. Thus, this case study had three goals. 1) To determine whether GH, comparatively to PH, would increase TBW before exercise. 2) To determine whether GH would improve thermoregulatory (sweat rate and rectal temperature) and cardiovascular (heart rate) functions during a 2 hr cycling exercise at 65% VO_2max. 3) To evaluate whether GH would improve endurance performance. It was hypothesized that GH would increase TBW, decrease rectal temperature, enhance endurance performance, but have no effect on sweat rate and heart rate. The results of this case study would help determine whether it is worth conducting further studies on GH in highly trained athletes when they exercise in a thermoneutral climate.

METHODS

Subject and Informed Consent

One highly trained male triathlete participated in this experimental project. He particpated on a voluntary basis and was not compensated financially. His age, BW, body surface area, peak power output (PPO), percentage of VO_2max corresponding to ventilatory threshold 2 (VT_2), and VO_2max were 27 yrs, 72.15 kg, 1.85 m^2, 400 Watts, 85% VO_2max and 4.6 L/min, respectively. Over the past 16 weeks prior to this study, the subject dedicated an average of 25 hr/week to his training. In the year 2000, his training volume, expressed as the yearly total number of km/sport, was 800, 8000 and 2200 km of swimming, biking and running, respectively. The subject's personal best time for an Olympic triathlon (1.5 km of swimming, 40 km of biking and 10 km of running) was 1:49:44 (hr:min:s). In comparison, the 2001 triathlon World Championships was won with a time of 1:48:01. Prior to undertaking this study the subject first completed a health history questionnaire to screen for

predisposing health and medical conditions that would contraindicate exercise testing of any type. The study procedures and risks were then fully explained to the subject, and the subject then consented to participate and signed a written informed consent. The experimental protocol was approved by the local Research and Ethics Committee of the Faculté d'éducation physique et sportive of the Université de Sherbrooke.

Preliminary Testing

One week before his first trial the subject underwent a measurement of VO_2max, VT_2, and PPO on a computer controlled, speed independent, cycle ergometer (Ergoline ER 900, Jaeger, Europe) that was modified with a road handlebar and the subject's seat and cleat pedals. For this purpose, a continuous graded test was utilized. The subject warmed-up on the ergometer by cycling for 5 min at a load of 75-100 Watts. Following a brief rest period (~1 min), the subject then began to cycle at a load of 100 Watts for 2 min. Thereafter, the load was step-incremented by 30 Watts/min. The test ended either when the subject claimed exhaustion or at the exact moment his pedal frequency attained 59 rev/min. During the test the subject wore an airtight face mask (Hans Rudolph, USA) on which a tripleV digital volume sensor was connected. The tripleV was linked to an Oxycon Pro (Jaeger, Europe) expired gas analysis system that was calibrated 30 min before the onset of the test with gases of known concentration. The Oxycon system was connected to a conventional high performance computer and calculations (average of each 15-sec interval) for VO_2, VE/VO_2, VE/VCO_2, $P_{ET}CO_2$ and RER data were performed by the Intellisupport software provided with the system. Attainment of VO_2max was validated when at least two of the following three criteria were met: 1) a plateau in VO_2 despite an increase in workload; 2) an RER equal ≥1.1, and 3) attainment of at least 90% of the age-predicted maximal heart rate (220-age). VO_2max was defined as the highest VO_2 value obtained during the test. VT_2 was determined using the criteria of an increase in both the VE/VO_2 and VE/VCO_2 and a decrease in $P_{ET}CO_2$ (17). For the test of VO_2max, PPO was defined as the last power output that was maintained longer than 30 s.

Familiarization Trial

Approximately 15 min after having completed the VO_2 max test, the subject underwent a familiarization trial consisting in 45 min of cycling at ~65% of individual VO_2max. The goal of this familiarization trial was to determine and confirm the workload to be employed in the exercise trials (i.e., the one that elicited ~65% VO_2max), and to familiarize the subject with the equipment and procedures employed in this study. The VO_2max test served to familiarize the subject with the endurance performance test. The subject had on many previous occasions performed graded tests to exhaustion similar to the endurance performance test employed in this study. In the last 4 weeks before his first trial, the subject completed 5 bike rides equal to, or longer than, 2 hr. Hence, the learning and training effects resulting from the execution of the first trial (i.e., 2 hr of cycling and the endurance performance test) were anticipated to be negligible and, therefore, to have little influence on the results of the second trial.

Pre-Experimental Protocol

Over the study period the subject continued his usual training. He refrained from any physical activity the day prior to both trials. Additionally, he refrained from strength training for the last 3 days prior to both trials and went to bed at the same time of the night prior to both trials. For the last 24 and 48 hr prior to the first trial, the subject kept a fluid and a diet log, respectively. Then he replicated these logs prior to the second trial. The day before each trial the subject refrained from consuming diuretic substances such as alcohol, tea, coffee, and chocolate. On the day of each trial he reported to the laboratory 90 min after having drunk 500 mL of water and eaten a white bagel (~200 Kcals). Consumption of the bagel and the ingestion of water were respectively designed to ensure sufficient energy level prior to the cycling exercises and equal hydration prior to the hyperhydration periods.

Experimental Trial

At weekly intervals after the familiarization trial, the subject returned to the laboratory at the same time of the day. The laboratory was continuously maintained at 25 °C, 38-42% relative humidity. Immediately after his arrival, he voided his bladder and was then weighed nude to nearest 50 g. Afterwards, to determine any possible side effect associated with the ingestion of the water and glycerol and placebo solutions, he rated on a scale of 1 (none) to 5 (extreme) different symptoms (abdominal bloating, cramp, nausea, headache and dizziness). Then the hyperhydration periods began. The protocol of hyperhydration utilized during GH and PH is shown in Table

1. At 0, 40 and 80 min the subject ingested either the glycerol or placebo solutions, which consisted of 29 g of glycerol (TwinLab, USA) mixed with 433 mL of diluted aspartame drink (Crystal Light, USA), and 433 mL of diluted aspartame drink, respectively. At 20 and 60 min he ingested 289 mL of distilled water. The glycerol (served as 6.6% solutions) and fluid were administrated in divided doses in the hope to minimize the incidence of side effect. By giving the glycerol as a 6.6 % solution every 40 min we hypothesized that it would diminish/eliminate the possibility that the subject developed nausea, headache or dizziness. Similarly, by administrating relatively small doses of fluid every 20 min we theorized that it would eliminate the possibility that the subject develop abdominal bloating or cramps. The glycerol and placebo solutions were given in a double-blind random fashion. Both the placebo and glycerol solutions were served at 4 °C and had the same color, taste and texture.

Table 1. Hyperhydration regimens.

Time (min)	Glycerol Hyperhydration	Placebo Hyperhydration
0	0.4 g glycerol/kg BW with 6 mL/kg BW of diluted aspartame drink	6 mL/kg BW of diluted aspartame drink
20	4 mL/kg BW of distilled water	4 mL/kg BW of distilled water
40	0.4 g glycerol/kg BW with 6 mL/kg BW of diluted aspartame drink	6 mL/kg BW of diluted aspartame drink
60	4 mL/kg BW of distilled water	4 mL/kg BW of distilled water
80	0.4 g glycerol/kg BW with 6 mL/kg BW of diluted aspartame drink	6 mL/kg BW of diluted aspartame drink
110	End of the protocol	
120	Beginning of the cycling exercise	

Distilled water was served at room temperature, that is at 25 °C. Immediately after having ingested the glycerol and placebo solutions, the subject rinsed his mouth with 50-100 mL of tap warm water (37 °C), which was then spat into a sink. The goal of this procedure was to remove any possible residual taste of glycerol. The subject was unable to differentiate between the two hyperhydration solutions.

To determine the changes in TBW over time during the hyperhydration periods, the subject, immediately after the rating of side effects, urinated in a graduated urinal at 18, 38, 58, 78 and 110 min. The changes in TBW were computed by subtracting the accumulated volume of urine produced from the accumulated volume of fluid ingested. Insensible water loss was assumed to be similar between trials. At 111 min a nude BW was taken. Then, in the 7 min that followed, the subject dressed himself and was instrumented with a rectal probe for the determination of rectal temperature and an electrode for the determination of heart rate. Then he mounted the bike and rested calmly on it for 2 min after which time a measure of rectal temperature, heart rate, perceived exertion (Borg scale, 20-point scale, 6: very, very light; 20: very, very hard), perceived thirst (11-point scale, 1: none; 11: extreme) and abdominal discomfort (5-point scale, 1: none; 5: extreme) was taken.

The 2 hr cycling exercises started exactly 120 min after the onset of the hyperhydration periods. To ensure similar exercise intensity between trials, VO_2 was continuously monitored during the first 15 min of both bouts of exercise. And, if necessary, the workload was adjusted to provoke the desired consumption of O_2. Throughout exercise, the subject maintained his pedal frequency between 80-90 rev/min. A fan located 2 m in front of the bike circulated air at a low velocity. Measures of perceived exertion, perceived thirst and abdominal discomfort were taken at 18, 38, 58, 78, 98 and 118 min followed by heart rate and rectal temperature, 2 min later. Every 20 min, and this up until min 100, the subject ingested 166 mL of sports drink (Gatorade, USA) concentrated at 6%, which was given at 25 °C to minimize its cooling effect. Such a volume of fluid (i.e., 500 mL/hr) was specifically chosen as it has been shown to reflect the actual rate of fluid intake of most endurance athletes during exercise (6). The subject was free to stop at any time during exercise to pass urine, except when the next collection of measures was within the next 10 min.

Immediately after the cycling exercises, the subject urinated, removed his cycling short and shoes, toweled dry, and was weighed nude. Then he put back on his cycling short and shoes, mounted the bike, and rested calmly on it for 1 min. At the end of this resting period a measure of heart rate and rectal temperature was taken. The elapsed time between the end of cycling exercises and the onset of the endurance performance tests was 5 min. The subject began the endurance performance tests at the load previously employed during the 2 hr cycling exercises plus 25 Watts. The load was subsequently increased by 25 Watts every 3 min until he claimed complete exhaustion or at the exact moment his pedaling frequency attained 59 rev/min. Rectal temperature and heart rate were measured at the end of each plateau and at the end of the tests. The subject was not allowed to stand on the pedals. He was encouraged to a similar extent in both tests and was made aware of the elapsed time. At the exact moment he stopped the tests, the time was taken. For this performance bout, PPO was computed using the following formula: last workload completed for the entire 3 min + ((total time [s] in the last workload which was not entirely completed/180 s) x 25 Watts). The subject then took a period of 3-10 min for cooling down after which he was stripped of any experimental equipment.

Measurement of Rectal Temperature

Immediately after the hyperhydration periods, the subject inserted a rectal probe (YSI, USA) 15-cm beyond his anal sphincter with the aid of a water-soluble lubricant (HR Lubricating Jelly, USA). The rectal probe was connected to a YSI tele-thermometer (model 46 TUC, USA). The correct placement (depth) of the probe was verified every 20 min during exercise. The tele-thermometer was adjusted to the red line before each trial in order to ensure the reliability of the measures.

Measurement of Heart Rate

Heart rate, using a 5 s sampling rate, was measured in real time using a computerized interface unit (Polar Advantage, Polar, USA). To facilitate signal conductivity, an electrolyte gel (Signa Gel, Parker Laboratories, USA) was applied on the electrode before installation.

Measurement of Sweat Rate

Sweat rate was computed using the following formula: (BW before exercise – BW after exercise [bladder emptied] + total volume of fluid consumed during exercise) – any urine loss during exercise). No correction was made for insensible water loss and the loss of mass associated with the respiratory exchange of O_2 and CO_2, and all were assumed to be identical between trials.

RESULTS

Hyperhydration Period

Similar initial BW (PH: 72.9; GH: 72.85 kg) indicate that the subject started the hyperhydration periods in a similar state of hydration. During both hyperhydration trials the subject ingested 1,875 mL of fluid. Figure 1 presents the changes in TBW and the urine volumes produced over time during GH and PH.

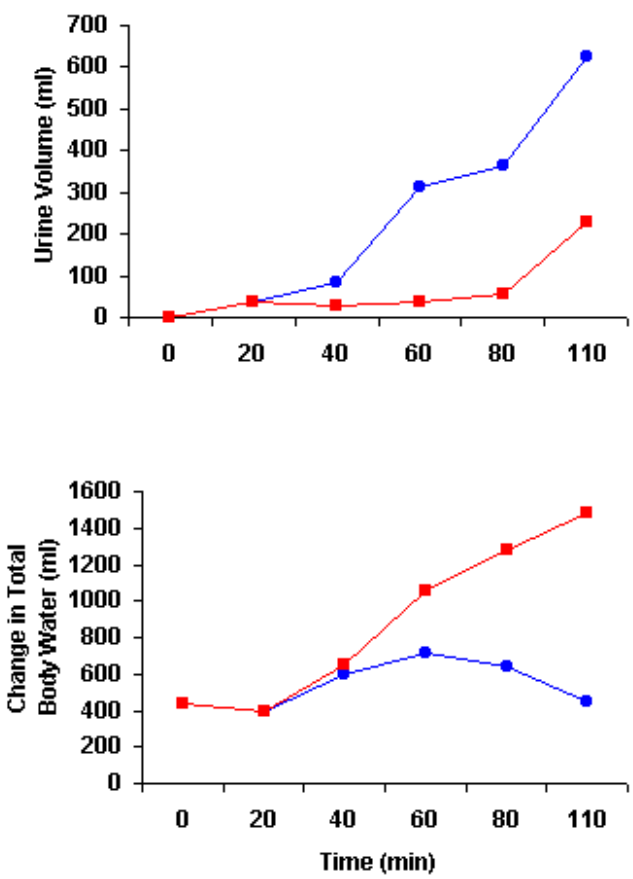

Figure 1: Changes in total body water (bottom) and urine volumes produced (top) over time (min) during placebo (blue circle) and glycerol (red square) hyperhydration.

As expected, both GH and PH produced a state of hyperhydration prior to the onset of the cycling exercises. In both trials TBW increased to a similar extent until 40 min. With PH TBW peaked at 60 min

after which time it steadily decreased to reach a final value at 110 min of 453 mL, compared to a peak of 1,486 mL with GH. Thus, compared to PH, the addition of glycerol to the diluted aspartame drinks increased TBW by an additional 1,033 mL. With PH urine volumes steadily increased over time to reach a peak value at 110 min of 625 mL, for an accumulated volume of 1,422 mL. In contrast, GH urine volumes remained similar (within 28-56 mL) to 80 min, reaching a peak value at 110 min of 230 mL for an accumulated volume of 389 mL. Of practical importance is that at no time points in both trials did the subject report abdominal bloating, cramps, dizziness, headache or nausea.

Cycling Exercise

In both trials the subject exercised at a work rate of 210 Watts, which elicited a VO_2 of 3,070 mL/min, corresponding to 66.8% of VO_2max. In both trials the subject ingested a total of 830 mL of Gatorade. Heart rates and rectal temperatures measured during rest, immediately prior to undertaking the cycling exercises, and during exercises every 20 min, are shown in Figure 2. Heart rate at the onset of exercise with GH was lower with a value of 51 compared to 58 b/min with PH. From 0 to 20 min, heart rate increased to 117 b/min in both trials and then increased slightly to reach a final value of 125 and 123 b/min with PH and GH, respectively.

The subject began both cycling exercises with a similar rectal temperature (PH: 36.35; GH: 36.3 °C). With PH, rectal temperature increased rapidly to 37.2 °C at 20 min and then rose steadily over time to reach a final value of 37.85 °C. With GH, rectal temperature increased rapidly to 37.3 °C at 20 min, then increased to 37.4 °C at 60 min, after which time it stabilized to reach a final value of 37.43 °C.

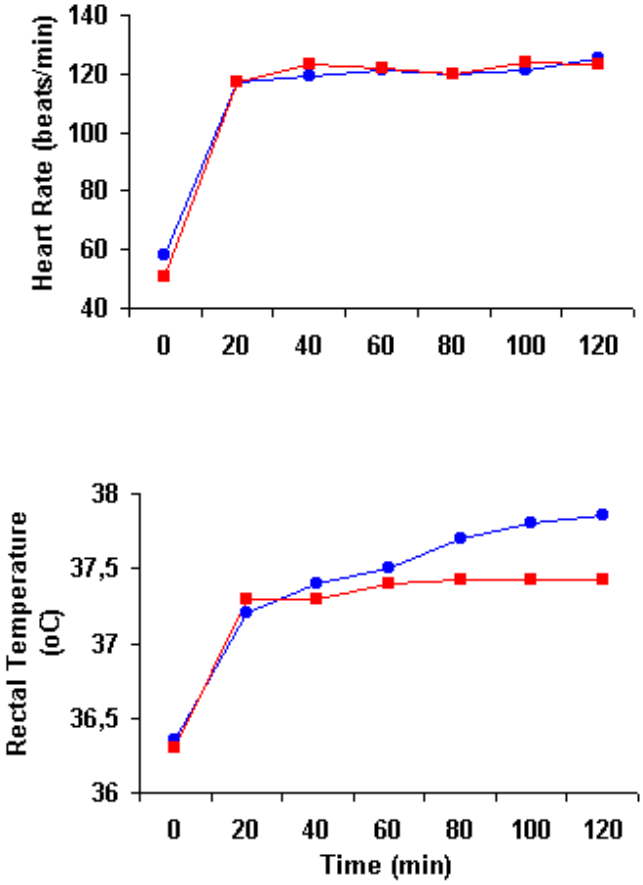

Figure 2. Heart rate (top) and rectal temperature (bottom) values at 20-min intervals during exercise with placebo (blue circle) and glycerol (red square) hyperhydration.

Total sweat rate with PH and GH was 2,040 mL (17 mL/min) and 2,000 mL (16.7 ml/min), respectively. During the cycling exercises, urine volume with PH and GH was 613 mL (5.1 ml/min) and 310 mL (2.6 mL/min), respectively. Accordingly, taking into account the amount of fluid ingested during exercise and the difference between trials in 1) fluid retention before exercise; 2) sweat rate and; 3) urine volume produced during exercise, the subject ended the GH trial with 1,375 mL more fluid, compared to the PH trial. Thus, the subject terminated the GH trial euhydrated. In contrast, he terminated the PH trial dehydrated by 2% of his BW. At no time points perceived thirst and perceived exertion values differed between trials. Additionally, at no time points in both trials did the subject report abdominal discomfort.

Endurance Performance Test

Comparatively to PH, the time to exhaustion was greater with GH (PH: 15.47; GH: 19.36 min). Consequently, PPO was greater with GH with a value of 373 Watts, comparatively to 342 Watts with PH.

In the 5 min that separated the end of the cycling exercises from the start of the endurance performance tests, heart rate with PH and GH declined by 53 and 47 b/min, respectively. Thus, at the start of the tests, heart rate was 4 b/min lower with PH than with GH. Maximal heart rate was identical between trials with a value of 170 b/min. From the end of cycling exercises to the start of the endurance performance tests, rectal temperature with

PH and GH decreased from 37.85 to 37.45 °C and from 37.43 to 37.25 °C, respectively. During the endurance performance tests, the rate of increase in rectal temperature with PH was 0.85 °C for a final value at exhaustion of 38.3 °C, whereas with GH it was 0.75 °C for a final value of 38 °C. Thus, even though the time to exhaustion was increased by 24% with GH, the subject finished this trial with a lower rectal temperature.

DISCUSSION

In the present study it was observed that, comparatively to PH, GH increased TBW by an additional 1,033 mL (14.3 mL/kg BW) over a 2 h period. This result highly contrasts with those of studies that have observed the effect of GH during a 2 h period. In fact, Freund et al. (11), Hitchins et al. (12), Riedesel et al. (16) and Montner et al. (14) have reported that GH, comparatively to PH, increased TBW over a 2 h period by ~ 250, 500, 275 and 600 mL, respectively. However, it must be noted that important methodological differences existed between these studies and ours. In fact, the first three studies (11,12,16) administrated the fluid (21-22 mL/kg BW) and glycerol (0.9-1 g/kg BW) within the first 30-40 min of the hyperhydration protocol. That of Montner et al. (14) administrated 1 g glycerol/kg BW as a 20% solution at 0 min and 0.2 g glycerol/kg BW as a 4% solution at 60 min with the remaining fluid (5 mL/kg BW of water) administrated at 30, 90 and 120 min. In the present study, we administrated 26 mL/kg BW of fluid with 1.2 g glycerol/kg BW. Glycerol (0.4 g/kg BW) was ingested as a 6.6% solution at 0, 40 and 80 min, with the remaining fluid (4 mL/kg BW of distilled water) ingested at 20 and 60 min. Evidently, any comparison with the above studies are difficult, as the reported results of fluid retention are means of a group of subjects, not individual results. However, Lyons et al. (13) reported individual results of additional retention of fluid provided with GH (compared to PH), and the highest value obtained by one subject (# 4) was 750 mL with a mean (6 subjects) of 520 mL. In this study, the glycerol (1 g/kg BW) and fluid (24.4 mL/kg BW) were ingested at 0 min and the measure of fluid retention taken after 2.5 hrs. As the protocol of hyperhydration with glycerol utilized in the present study produced, compared to that of the ingestion alone of water and diluted aspartame drinks, a high retention of fluid without producing any side effects, its use should be encouraged. However, additional studies using a protocol of hyperhydration identical to the one used in the present study will be required to validate our result.

An important finding of this study is that, comparatively to PH, the production of urine during the cycling exercise with GH was decreased by 300 mL, despite the fact that the subject began this trial with 1,033 mL more TBW. Thus, in the present study, it appears that the anti-diuretic effect of glycerol lasted until the end of the cycling exercise. The observation of a decreased urine output during exercise with GH would conflict with the observations of Montner et al. (15) and Latzka et al. (18) who reported that GH, compared to PH, did not reduce urine production during exercise. Pragmatically, the fact that GH decreased urine output during exercise more than PH would imply that this strategy could reduce the incidence of having to stop to pass urine during exercise, which is especially important for athletes seeking high performance.

Despite that GH enabled the subject to begin the cycling exercise with a greater reservoir of water, it was observed that it had no substantial effect on heart rate and sweat rate. Others have also demonstrated that heart rate (12,13,18) and sweat rate (12,15,18) were unaffected by GH. However, not all studies are in agreement with these findings. Indeed, compared to PH, Montner et al. (15) showed that GH significantly decreased heart rate by 2.8 and 4.4 b/min in study 1 and 2, respectively. In the first study, GH increased TBW by 660 mL before exercise, whereas in the second TBW was increased to a similar extent in both trials. Lyons et al. (13) demonstrated that GH increased sweat rate during a 90 min run at 60% VO_2 max conducted in the heat. In this study, GH increased TBW by an additional 520 mL before exercise. Unfortunately, none of these studies systematically measured the changes in plasma volume during exercise. However, values of hemoglobin and hematocrit revealed no significant difference between the glycerol and placebo trials. Comparatively to PH, GH has been shown to not significantly increase plasma volume during rest and exercise (11,12,18). According to Latzka et al. (19), hyperhydration either with water or glycerol would elicit a plasma volume expansion that is proportional to the increase in TBW x 7.5% (the percentage of TBW in the plasma). Consequently, if GH,

comparatively to PH, were to increase TBW by an additional 500-660 mL in an individual, then his/her plasma volume would only be increased by approximately 38-49 mL. This small volume difference between treatments is probably beyond measurement resolution (11). Nose et al. (20) in 1990 examined the effect of plasma volume expansion during 50 min of cycling exercise at 60% VO_2max in a thermoneutral (22 °C) and warm (30 °C) climate. A no infusion trial was compared the infusion of a 0.9% NaCl solution at a rate of 0.29 mL/kg BW/min. Compared to the control trial, the infusion trial elevated plasma volume levels by ~8% (280 mL) at the end of exercise, which, interestingly, had no effect on heart rate in the thermoneutral climate and on sweat rate in both climates. Accordingly, though possible, it is unlikely that an increase in plasma volume of a magnitude of 38-49 mL could account for the decrease in heart rate and increase in sweat rate observed in the study of Montner et al. (15) and Lyons et al. (13), respectively.

Comparatively to PH, the rectal temperature at the end of the cycling exercise with GH was decreased by 0.42 °C. Concomitantly, the subject maintained euhydration with GH, but was dehydrated by 2% of his BW with PH. Sawka and Coyle (21) reported that the magnitude of increase in core temperature during exercise ranges from 0.1-0.23 °C for every percent BW lost above that of euhydration, which would be in line with the difference in rectal temperature observed between GH and PH (2% x 0.21 °C: 0.42 °C). Thus, in the present study, GH proved better than PH in reducing core temperature because it maintained a better state of hydration. At the end of the cycling exercises, total sweat rate was similar in both trials. However, as rectal temperature was higher with PH compared to GH, the sweat rate for a given rectal temperature was lower with PH. It has been shown that dehydration reduces the ability to dissipate heat because it increases plasma osmolality, which reduces skin blood flow (22). Comparatively to PH, GH has been demonstrated to increase plasma osmolality by more than 10 mOsmol/kg during exercise (18). However, as glycerol should penetrate osmosensitive cells, the increase in osmolality resulting from the ingestion of glycerol is not expected to alter the control of thermoregulation (18). Lyons et al. (13) are the only ones who found lower (- 0.7 °C) rectal temperatures with GH, compared with PH. However, such a result is difficult to explain since the difference in dehydration between treatments at the end of exercise was of the order of only 0.24% of BW (placebo: 0.3%; glycerol: 0.056% of BW).

Compared to PH, it was observed that GH increased endurance performance by 24%. This result agrees with those of other studies, which reported that GH was associated with an increase in time trial performance (12) and time to exhaustion (15). However, none of these studies was able to identify the exact mechanism by which GH improved exercise capacities: no change in any single variable was found that could have explained the connection between the fluid retention responses and the enhanced exercise capacities. Interestingly, in the second study of Montner et al. (15), GH did not further increase fluid retention comparatively to PH, but times to exhaustion were nevertheless increased by 24% with this treatment. Hence, it would be tempting to suggest that the use of glycerol as an energy substrate could have contributed to the increase in exercise capacity observed in these studies. In that respect, Scotto et al. (23) have recently reported that during 2 hrs of cycling exercise conducted at 68% VO_2max, the rate of exogenous glycerol oxidation after the ingestion of 1 g glycerol/kg BW was 0.15 g/min. This amount of glycerol oxidation was estimated to contribute 7% of the energy yield. The authors concluded that "there is no justification for encouraging ingestion of glycerol as an energy supplement." Others (24,25) have concluded that after the ingestion of 1 g glycerol/kg BW the oxidation of exogenous glycerol could contribute to a maximum of 5 (25) and 8% (24) of the energy yield, which has been shown as being insufficient to improve exercise capacity (24).

In the present study, the increase in endurance performance with GH compared to PH was associated with a better state of hydration and a reduced rectal temperature both at the onset and end of the endurance performance test. Below et al. (4) had subjects perform a time trial (~10 min) immediately after they had pedaled for 50 min at 80% VO_2max in a warm climate. During the cycling exercises either 1,300 or 200 mL of fluid were provided to subjects, which produced a state of dehydration of 0.5 and 1.8% of BW, respectively. Time trial performance was increased in the trial where dehydration was minimized and was associated with a

reduced rectal temperature both before (0.21 °C) and at the end (0.17 °C) of the time trial. Compared to maintaining euhydration during a 1 hr cycling exercise at 70% VO_2peak in the heat, Walsh et al. (5) showed that dehydration as low as 1.8% of BW reduced time to exhaustion by 36% during a subsequent bout of exercise at 90% VO_2peak. However, the increase in time to exhaustion was not associated with a reduced rectal temperature.

Conclusion

Compared to PH, it was observed that GH increased pre-exercise TBW by 1,033 mL and attenuated the loss of fluid through urine during exercise by 100% (300 mL). The addition of glycerol to the drink enabled the subject to end the cycling exercise euhydrated, compared to 2% dehydration with PH. Despite this fact, sweat rate, heart rate and perceived exertion were similar between trials after 2 hrs of cycling. However, at the end of the cycling exercise with GH, rectal temperature was decreased by 0.42 °C. This study's results (less dehydration, decreased core temperature and enhanced endurance performance) suggest that for those who would be interested to hyperhydrate when exercising in a 25 °C environment the addition of glycerol to the ingested fluid (6.6% glycerol solution) would be a good option, as it might reduce dehydration, thereby reducing homeostatic disturbance. And, as a result of this, exercise capacity could be increased and recovery from exercise accelerated/facilitated, which is especially important for endurance athletes who perform more than one training session per day.

The results of the present investigation encourage, in a thermoneutral climate, further studies on the effect of GH in highly trained athletes. The next step, using a procedure of hyperhydration identical to the one used in the present study, would be to utilize exercise protocols that would 1) better mimic real athletic events and/or; 2) put greater stress on the cardiovascular and thermoregulatory systems and; 3) measure endurance performance with time trials, which are more reliable than tests to exhaustion. For instance, how GH would affect thermoregulatory and cardiovascular functions and endurance performance during a simulated sprint duathlon (5 km of running, 30 km of biking, 5 km of running) would be interesting to determine. Dehydration is high in elite athletes at the end of a marathon race (personal observation). Consequently, it would be relevant to determine whether or not GH could prove useful during such exercise. For this purpose, a time trial consisting in 30-35 km of running could be utilized.

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