Glycerol Hyperhydration and Endurance Running Performance in the Heat

Thesis

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By

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ABSTRACT

Glycerol hyperhydration has been used to induce fluid retention prior to exercise to offset dehydration. Conflicting results exist on whether it reduces cardiovascular and thermal strain while improving endurance performance. Few studies have used a protocol that mimics athletic races; none have been done on running performance. Six endurance trained runners ($\text{VO}_{2\text{peak}} = 60.7 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) completed a run at a self-selected pace, estimated to take 1 hour. Temperature was set at 30°C and 50% humidity. A randomized, double-blind, cross-over design was used for glycerol (Gly) ingestion, given as $1.2 \text{ g}\cdot\text{kg}^{-1}$ bodyweight with a total fluid ingestion of $26 \text{ ml}\cdot\text{kg}^{-1}$ bodyweight, or placebo (PI) of water ingestion of an equal amount, beginning 2.5 hours prior to exercise. Glycerol hyperhydration did not result in increased fluid retention over water hyperhydration (Gly = 977 ml, PI = 391 ml, $p > 0.05$). Time to complete the run was not different between trials (Gly = 4074 s, PI = 4079 s, $p > 0.05$). Heart rate, core temperature, and RPE were not different between trials at any distance or 5 min interval during the run. Our main hypothesis was not supported; during a self-selected pace protocol, runners did not experience an increase in performance with prior glycerol ingestion.

Dedicated to my wife, Ashlee

Her support has been as never-ending as my need for it

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CHAPTER 1

INTRODUCTION

Dehydration and hyperthermia can have marked effects on the cardiovascular and thermoregulatory systems. Heart rate increases and stroke volume decreases as individuals dehydrate and core temperatures increase [1, 2]. This can result in decreased cardiac output and negative effects on an individual's ability for heat dissipation [3]. This is important in athletes as fatigue can occur with core temperatures around 40°C [4]. Despite core temperature, performance can also be affected by dehydration equal to 2% of body weight [5]. To maintain performance, dehydration must be offset by ingesting fluid to match sweat rates [2]. Runners do not typically ingest this amount of fluid as it can reach over 1.5 liters per hour, resulting in voluntary dehydration [6]. Glycerol hyperhydration can lead to an increase in fluid retention of up to 1.5 liter [7]. This excess fluid could offset dehydration during exercise. Studies have currently shown conflicting results on whether the cardiovascular and thermal strain is reduced with glycerol hyperhydration or whether performance is actually increased [7-19]. Glycerol hyperhydration seems to be more beneficial during exercise in hot environments [15] and when fluid intake during exercise does not meet sweat rate [13]. As athletes may adopt glycerol hyperhydration as a way to maintain performance, studies need to test it using a protocol that mimics an athlete's competitive event. The purpose of this study is to test glycerol hyperhydration versus water hyperhydration using a self-selected running protocol in a hot

environment with experienced endurance trained runners. Cardiovascular and thermoregulatory parameters and time to complete the set distance will be measured. We hypothesize that glycerol hyperhydration will lead to greater fluid retention than water hyperhydration, that cardiovascular and thermoregulatory parameters will not be different during the run due to the self-selected pacing, and that the time to complete the run will be faster with glycerol hyperhydration.

CHAPTER 2

REVIEW OF LITERATURE

Cardiovascular effects of Dehydration and Hyperthermia

Dehydration and hyperthermia both, alone and together, can have marked effects on the cardiovascular and thermoregulatory systems. As body temperature increases, skin blood flow (SKBF) increases and sweating is initiated for heat dissipation [1, 20]. Cardiovascular drift is proportional to the level of dehydration and rise in body temperatures [2]. During prolonged exercise heart rate (HR) parallels the increase in body temperature [1], decreasing stroke volume (SV) [21]. Prolonged sweating also reduces SV as total body water and blood volume is reduced, compromising cardiac output (CO) [2, 22].

During moderate exercise, dehydration equal to 4% body weight loss will not affect cardiac output, nor will hyperthermia (39.3°C) [22]. However, during vigorous exercise, 3% dehydration can decrease CO [23]. When hyperthermia and dehydration are superimposed systemic vascular resistance (SVR) is increased to further attenuate the decrease in CO [22], yet possibly lowering the amount of heat dissipation [3]. Heat dissipation is of particular importance as athletes tend to fatigue at body temperatures of ~40°C despite similar starting body temperatures [4]. Even without body temperatures of ~40°C, athletes may fatigue while dehydrated and hyperthermic as a maximal HR is achieved yet mean arterial pressure cannot be sustained [22].

Dehydration can also result in hyperosmotic blood (plasma osmolality ≥ 297) [24]. Hyperosmotic blood limits heat dissipation by delaying the onset of sweating by requiring a higher body temperature to elicit sweating [25]. It also increases body temperature at which cutaneous vasodilation occurs [25], limiting SKBF at any body temperature [3]. Fortney suggests that hypovolemia may intensify these effects [3].

Performance effects of Dehydration

Armstrong et al. has shown that dehydration of 1.6% of body weight alone, through the use of furosemide (diuretic), can decrease performance in a 5000 meter race [26]. Statistical Analysis showed that a 1% decrease in body weight decreased time by 0.39 minutes and 1.57 minutes for the 5000 and 10000 meter time trial, respectively [26]. Despite decreases in plasma volume, no changes in VO_2 at max or submax intensities were seen [26]. It would be expected that increased thermal strain over longer durations would cause an additive effect on performance decrement. It is also important to note that when starting an event euhydrated these performance decrements may not be so severe until similar dehydration occurs during the event.

In 1992, Montain and Coyle showed that cycling at 60% of $\text{VO}_{2\text{max}}$ at 32.7° C and 50% humidity for 2 hours resulted in increased esophageal temperature (T_{es}) correlating to the loss in body weight [2]. As fluid intake more closely matched sweat rate, forearm blood flow (FBF) and CO was better maintained, and T_{es} was lower [2]. If fluids were not replaced some subjects could not complete the exercise and had higher final RPE's [2]. These differences were not noticeable until after the first hour of exercise and were only apparent when subjects were dehydrated greater than 2.3% of body weight [2]. They concluded that fluid ingestion attenuated hyperthermia by promoting higher SKBF which should allow for continued heat dissipation [2].

Dehydration during a shorter event is possible if thermal strain is also introduced. Walsh had subjects cycle at 70% of VO_2peak at 30°C and 60% humidity for 60 minutes, followed by a test to exhaustion at 90% of VO_2peak [5]. Subjects that dehydrated to 1.8% of body weight had higher ratings of perceived exertion and shorter time to exhaustion than subjects who maintained euhydration [5]. No circulatory or thermoregulatory parameters were different [5], similar to Montain within the first hour of exercise [2]. A mechanism for fluid to increase performance is unclear, but may be related to the central nervous system [5]. Authors suggest that fluid ingestion to prevent dehydration is probably beneficial even in endurance events lasting 60 min [5].

These studies suggest that dehydration around 2% of body weight can negatively affect performance in both temperate and hot environments despite the mode of dehydration. Proper hydration may be important for performance maintenance in short events, and sustained euhydration in events lasting an hour or more despite not seeing any changes in thermoregulatory, circulatory or metabolic parameters. The American College of Sports Medicine currently recommends ingesting fluids to not incur a greater than 2% loss of body weight during the exercise bout [27]. With sweat rates reaching and exceeding 1.8 l/hour when conditions are hot and the intensity is high, a 70 kg man would need to consume a minimal of 400 ml/hour [27]. Armstrong showed that even a 1% loss of body weight would have a meaningful decrease in performance [26] while Montain suggests that the optimal rate of fluid replacement to attenuate cardiovascular drift is to match sweat loss [2]; this would increase the necessary fluid intake to 1.1-1.8 l/hour.

Voluntary Dehydration

Despite having adequate amounts of fluid available, athletes still tend to become dehydrated [6]. In 1997, Armstrong had subjects walk at 36% of VO_2max for 90 min in 33°C and

56% humidity [28]. Euhydrated subjects who were able to drink water ad libitum chose to ingest very little water and experienced a final dehydration of 1 liter [28].

These results should not be surprising. In a review, Noakes explained that an athlete's fluid intake is seldom more than 500 ml/hour, and there is little likelihood that it would reach 1 l/hour [29]. It appears the level of voluntary dehydration is proportional to the degree of stress imposed on the body [30]. With high sweat rates, this lack of fluid ingestion lends itself to voluntary dehydration and possible performance decrements. One possible reason behind voluntary dehydration mentioned by Noakes may be the symptoms of 'fullness' and increased discomfort experienced by athletes with fluid ingestions >800 ml/hour, with running reducing the desire to drink more than cycling [29]. One reason Armstrong may have seen such high amounts of fluid ingestion in the hypohydrated subjects is that the low level of intensity that subjects were exercising made fluid ingestion easier [28].

Recently Passe tested runners on their ability to perceive sweat loss and fluid intake and whether they matched them during a race [6]. 8 seasoned marathoners participated in a 10 mile race at 20.5°C and 76.6% humidity [6]. They were given the opportunity to drink fluids at miles 2, 4, 6, and 8, as it was handed to them in a 708ml water bottle to minimize change of pace [6]. Sweat rate during the race equaled 21.6 ml/kg/hour while subjects perceived it to be 12 ml/kg/hour [6]. Subjects only replaced 30.5% of sweat loss and ended the run dehydrated to 1.9% of body weight [6]. Subjects' perception of what they consumed was a reasonable approximation; however, the perception of fluid loss was only 42.5% of actual loss [6]. It is possible to see that even seasoned runners are not aware of sweat loss during running and cannot gauge necessary fluid intake without prior knowledge of sweat loss. Whether conditions included hot [28] or temperate [6] environments, subjects chose to limit fluid intake and become dehydrated.

Methods for limiting Dehydration

If athletes are to perform to the best of their ability, then levels of euhydration must be maintained throughout exercise or competition. The American College of Sports Medicine lists nude body weight differences from pre-exercise to post-exercise as a good way to determine sweat losses [27]. If an athlete is able to know how much sweat is lost during a 60 minute exercise bout at similar intensity and environmental conditions of the future exercise bout, then reasonable estimations of fluid intake can be made. This, however, does not change the fact that large fluid ingestions might be avoided due to other reasons [29]. If fluid ingestion cannot prevent dehydration then other methods need to be implemented.

Glycerol and Hyperhydration

Glycerol's use as an osmolyte had previously been noted for its therapeutic uses in relieving intracranial and intraocular pressures [31]. Ingested glycerol is passively absorbed through the stomach and small intestine [31]. Glycerol diffuses through all fluid compartments, although not crossing the blood brain barrier [31]. As glycerol passes through the kidney it is reabsorbed through the proximal and distal tubule [32], increasing the medullary gradient and allowing water to be reabsorbed [33], increasing both extracellular and intracellular water [34]. This decreased water excretion and subsequent hyperhydration, termed glycerol hyperhydration, occurs independently of hormonal responses [33, 34]. Hyperhydration between glycerol and desmopressin have been shown to be similar, confirming that glycerol acts on the kidney through decreased free water clearance [8]. In 1987, Riedesel et al. began a novel approach in the use of glycerol's osmotic properties to induce hyperhydration over prolonged periods of time [35]. Riedesel et al. showed that ingesting 1.0 gram of glycerol per kilogram of body weight while ingesting 21.4 ml of fluid per kilogram of body weight led to higher fluid

retention over 4 hours than fluid alone [35]. Nelson suggests that a total body water increase of 1000ml with glycerol will increase blood volume by 125 ml, and subsequently increase plasma volume (PV) by 75ml [36]. That is a 2.5% increase in PV with glycerol, an amount supported by Hitchins who saw a 100ml PV increase [9]. This extra availability to water may prove beneficial when circulatory demands are high or when dehydration would begin to hinder thermoregulatory responses.

Glycerol and Performance

Since 1983, glycerol has been studied for its possible effects on exercise performance [37]. Both Miller et al. [37] and Gleeson et al. [38] tested the ingestion of 1.0 g/kg body weight of glycerol on endurance performance and both concluded that glycerol does not improve endurance performance as it had done in the rat. The metabolism of glycerol in the liver as a gluconeogenic substrate was too slow to be ergogenic [37].

Although glycerol as a gluconeogenic substrate did not improve performance, glycerol as a hyperhydrater still held promise. Several studies following Riedesel tested glycerol's hyperhydration ability [10, 33, 34], confirming an increased fluid retention of 0.9-1.2 L with 1.0-1.1 g/kg body weight of glycerol with a total fluid intake of 21-37 ml/kg bodyweight. Knowing that glycerol could increase fluid retention allowed further studies on how glycerol hyperhydration might affect cardiovascular and thermoregulatory parameters during exercise. Lyons first showed that glycerol increased sweat rate and decreased core temperature during cycling at 42°C at 60% of VO_{2max} [7]. Montner showed decreased heart rates and increased stroke volumes during cycling for 110 min at 44% VO_{2max} in 24°C [10]. However, Latzka showed no differences in any parameter for subjects completing 2 hours on a treadmill at 45% VO_{2max} and 35°C [13]. It appears that differences in exercise protocol and hyperhydration protocol (2 hour protocol for Lyons [7] and Montner [10], 1 hour for Latzka [13]) may account for the

conflicting results. Also, Latzka had subjects remain euhydrated during the exercise by ingesting fluids [13]. These studies suggest that when water ingestion during exercise can meet sweat rate and /or when large amounts of fluid ingestion in a short time frame prior to submaximal exercise can be tolerated, glycerol hyperhydration may not have any thermoregulatory or cardiovascular benefit. This does not discount glycerol hyperhydration prior to maximal exercise when fluid replacement cannot meet sweat rates and large volumes of fluid ingestion completed only 30 minutes prior to exercise cannot be tolerated.

In 1996, Montner showed the first performance increase with glycerol hyperhydration [11]. Cycling at 60% VO_{2max} until exhaustion at 24°C, the glycerol trial had a 21% increase in performance [11]. However, two subjects saw much larger increases in performance than most, who saw little or decreased performance. Further research tried to verify this performance increase. In 1998, Latzka did not see improvement in time to fatigue or thermoregulatory parameters for subjects walking at 55% VO_{2max} in 35°C [12]. Their 30 min hyperhydration period, 30 min prior to exercise, is shorter than most, possibly being a reason for the lack of difference.

With questionable results from Montner, and Latzka using a short hyperhydration phase, additional studies needed to be done. Inder had triathletes cycle at 25°C for 1 hour at 70% VO_{2max} followed by an incremental test to exhaustion [8]. They saw no performance differences. In this case the hyperhydration phase was 4 hours long and used less fluid than other studies [8]. Riedesel had also already shown that 64% of water is loss at 4 hours post hydration, possibly reducing glycerol's effectiveness [35].

In 1999, Hitchins et al. had subjects ingest glycerol as 1 g/kg body weight with 22 ml/kg bodyweight fluid in 30 min, 2.5 hours prior to cycling in 33° C, 57.8% humidity at 90% of lactate threshold for 30 minutes followed by 30 minutes of cycling to complete as much work as possible [9]. A 5% increase in work done was seen during the glycerol trial [9]. Hitchins showed

no decrease in heart rate, increase in sweat rate, or decrease in core temperature [9] as seen in previous studies [7, 11]. It is worth noting that during the variable power phase, the increased power output may have required a high heart rate and maintained a high core temperature, and so a thermoregulatory and cardiovascular advantage could not be ruled out.

At this point it seems that glycerol hyperhydration may increase performance when taken 2-2.5 hours prior to exercise in hot temperatures. This seems to be the most appropriate as ingesting large amount of fluid 1 hour prior to maximal exercise may not be well tolerated. Cardiovascular and thermoregulatory changes seem to be the most likely reasons for increased performance but have yet to be shown.

Finally work in 2001 by Anderson et al. saw reduction in cardiovascular strain and increased performance [14]. Subjects cycling at 98% of lactate threshold for 90 min followed by a 15 min variable power phase in 35°C performed 5% more work with glycerol hyperhydration [14]. Performance may have been due to decreased rectal temperature, increased forearm blood flow and decreased HR at 78 min [14]. In contrast to Laztka [13], these results were seen despite subjects ingesting ~1 L/hour of fluid during exercise [14].

At this point performance had only been measured using lab protocols that do not match how competitive events are contested. Races are won by the individual who can complete a set distance in the shortest time. If glycerol hyperhydration is to be used by athletes, it needs to be tested in a way that mimics the athlete's actual event. This was first done by Coutts in 2002.

Coutts et al. had triathletes compete in an Olympic distance triathlon to observe performance in a field setting with glycerol hyperhydration or placebo [15]. The randomized crossover design had temperatures of 30.5°C and 46% humidity the first testing day and 25.4°C and 51.7% humidity the second day, an unplanned occurrence [15]. Coutts was able to show

that during the hot day, glycerol provided more of an advantage than during the warm day [15]. Performance was improved 2.1% on average, but only during the last stage, the 10 km run [15].

Due to the lack of control in the Coutts study more research is needed. Marino used a lab test where subjects self-selected their pace during a 1 hour cycle at 34.5°C [16]. Sweat rates were higher with glycerol hyperhydration; however this did not translate into decreased core temperature or improved performance, possibly due to the high humidity resulting in sweat dripping off the body [16]. Authors claim that the lack of performance difference was due to the self-paced protocol allowing subjects to use pacing strategies, where an externally fixed load would force proportional increases in physiological responses [16]. It seems that if glycerol decreased cardiovascular strain at a given intensity [14], subjects should have been able to complete more work despite similar parameters.

Wingo used a 30 mile bike race to test performance with glycerol hyperhydration [17]. Three 10 mile loops were completed at 28°C [17]. Only thirst sensation and environmental symptoms were lower for the glycerol trial, possibly due to the lower dehydration that occurred in the glycerol trial versus the water trial (2.2% of bodyweight, 3% of body weight, respectively) [17]. Authors identified the 8 min rest between loops to collect data as leading to a probable washout of any differences that may have existed if the race was continuous [17].

The three studies using self-selected pace protocols [15-17], two of which used a racing situation [15, 17], saw mixed results. Lack of temperature control for Coutts questions improvement with glycerol, and incremental testing may have washed out results for Wingo. Marino had high sweat rates but high humidity (63%) may have masked any other effects. Additional studies with self-selected pacing needs to be done to mimic competitive events.

Two additional studies have been done recently. Goulet in 2006 saw no changes in any parameter between glycerol and water hyperhydration [18]. Subjects cycled for 2 hours at 25°C

followed by a test to exhaustion [18]. Authors claim the lack of giving all glycerol at once to decreasing the osmotic effect and decreased the fluid retention normally seen, washing out any differences [18]. In 2007, Nishijima had runners cycle for 40 min at 73% lactate threshold, then 30 min at a variable intensity [19]. No differences were found between glycerol and water [19]. The fact that the runners were unaccustomed to cycling may have led to the lack of difference [19]. Another factor may be that both studies used moderate temperatures, which tends to minimize the effectiveness of glycerol.

Despite the numerous studies using glycerol to hyperhydrate subjects prior to exercise [7-19], there is a variety of contradictory results for both glycerol's effect on performance, as well as its effect on cardiovascular and thermoregulatory parameters. It seems that glycerol will hyperhydrate better than water if taken with a large enough dose of fluid 2-2.5 hours prior to exercise [7, 9-11, 14, 15, 17, 19, 33, 34]. This hyperhydration leads to an increase in body water of 0.3-1.5 liters [7, 9-13, 15, 17, 19, 33, 34]. Owing to the consensus that dehydration can have negative effects on performance [2, 5, 26, 27], glycerol's increase in body water should prove beneficial, particularly when fluid ingestion during exercise cannot meet sweat rates. One difference that may have lead to conflicting results in the literature is the difference in protocol used to measure performance. Most races are designed as fully self-selected pacing, completing a certain distance as fast as possible. Three fully self-selected pace protocols have been used so far in the literature, although all different [15-17]. If glycerol hyperhydration is to be used by competitive athletes, then it should be studied using a protocol that is most consistent with their competitive event.

Purpose of Study

Dehydration has detrimental effects on the cardiovascular and thermoregulatory systems, most likely being the cause of decreased endurance performance [2, 22]. During

competitive events, not all athletes ingest sufficient fluid to attenuate dehydration [6, 29]. In scenarios where fluid ingestion during exercise does not attenuate dehydration, glycerol hyperhydration may or may not be advantageous [7, 9, 10, 12, 15, 18, 19]. Glycerol hyperhydration has been shown to increase thermoregulatory parameters [7, 14, 16, 17], as well as have no effect [8, 9, 11-13, 15, 18, 19]. Exercise performance has also been shown to increase [9, 11, 14] or not change [8, 12, 13, 15-19]. Many of these conflicting results may be due to differences in the hydration protocol, whether fluids ingested during exercise met sweat rate, and the type of protocol used to test performance.

Glycerol studies to date that have focused on performance have used cycling or triathlon protocols [8, 9, 11, 14-19]. Few studies have tested athletes with a protocol that mimics their competitive event [15, 17]. No study has tested running alone, which is of interest as the weight gain through glycerol hyperhydration may attenuate the performance gain.

It is for the above stated reasons that this study will test the effect of glycerol hyperhydration on an endurance running protocol in the heat. We plan to test the following hypotheses:

1. Glycerol hyperhydration will result in increased body weight and larger fluid retention via decreased urine output than water hyperhydration.
2. Core temperature during a self-paced run will be similar following glycerol hyperhydration and water hyperhydration.
3. Heart rate during a self-paced run will be similar following glycerol hyperhydration and water hyperhydration during the run.
4. Sweat rate during a self-paced run will be similar following glycerol hyperhydration and water hyperhydration.

5. Rating of perceived exertion during a self-paced run will be similar following glycerol hyperhydration and water hyperhydration.
6. The time to complete the self-paced run will be shorter following glycerol hyperhydration than following water hyperhydration.

CHAPTER 3

INTRODUCTION

Dehydration and hyperthermia can have marked effects on the cardiovascular and thermoregulatory systems. Heart rate increases and stroke volume decreases as individuals dehydrate and core temperatures increase [1, 2]. This can result in decreased cardiac output and negative effects on an individual's ability for heat dissipation [3]. This is important in athletes as fatigue can occur with core temperatures around 40°C [4]. Despite core temperature, performance can also be affected by dehydration equal to 2% of body weight [5]. To maintain performance, dehydration must be offset by ingesting fluid to match sweat rates [2]. Runners do not typically ingest this amount of fluid as it can reach over 1.5 liters per hour, resulting in voluntary dehydration [6]. Glycerol hyperhydration can lead to an increase in fluid retention of up to 1.5 liter [7]. This excess fluid could offset dehydration during exercise. Studies have currently shown conflicting results on whether the cardiovascular and thermal strain is reduced with glycerol hyperhydration or whether performance is actually increased [7-19]. Glycerol hyperhydration seems to be more beneficial during exercise in hot environments [15] and when fluid intake during exercise does not meet sweat rate [13]. As athletes may adopt glycerol hyperhydration as a way to maintain performance, studies need to test it using a protocol that mimics an athlete's competitive event. The purpose of this study is to test glycerol hyperhydration versus water hyperhydration using a self-selected pace running protocol in a hot

environment with experienced endurance trained runners. Cardiovascular and thermoregulatory parameters and time to complete the set distance will be measured. We hypothesize that glycerol hyperhydration will lead to greater fluid retention than water hyperhydration, that cardiovascular and thermoregulatory parameters will not be different during the run due to the self-selected pacing, and that the time to complete the run will be faster with glycerol hyperhydration.

METHODS

Subjects

Nine healthy endurance trained males volunteered for the study. Three subjects did not complete the study, one dropped out due to illness and two were stopped due to high core temperatures. Only the data for the 6 remaining subjects is given. Subjects had been currently running 5 days or more and 35 miles (56.3 km) a week or more and have run competitive races throughout the last 3 years. Subjects had no history of heat injuries, prior use of glycerol, or history of abnormalities in swallowing, esophageal or bowel strictures, fistulas, or gastrointestinal obstructions. Testing occurred primarily in the fall, winter and spring months so subjects were assumed not to be heat acclimatized. Subjects gave their informed consent. The study was approved by The Ohio State University Biomedical Institutional Review Board.

	Mean	Std. Deviation
Age (years)	27.8	6.0
Weight (kg)	69.0	9.2
Height (cm)	174.0	3.5
BMI ($\text{kg} \cdot \text{m}^{-2}$)	22.7	2.2
Body Fat (%)	7.5	4.0
Relative $\text{VO}_{2\text{peak}}$ ($\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$)	60.7	6.2
Absolute $\text{VO}_{2\text{peak}}$ ($\text{l} \cdot \text{min}^{-1}$)	4.2	0.6

Table 3.1. Descriptive characteristics of the subjects. N = 6.

Study Design

Subjects underwent two treadmill performance runs estimated to last 1 hour. A double-blind, randomized, crossover design was used for the glycerol treatment. Prior to each run subjects ingested either a solution containing glycerol or a placebo solution of equal volume. Four to seven days prior to the first performance run, subjects underwent a $\text{VO}_{2\text{peak}}$ test. Seven to ten days following the first performance run, subjects underwent the second performance run.

Figure 3.1. Outline of testing days.

Oxygen consumption tests

Maximal oxygen consumption was determined using a maximal incremental treadmill protocol to volitional exhaustion. The test consisted of 1 minute stages with an initial stage set at 6 mph and 0% grade. Every minute the speed increases 0.5 mph. If subjects could go beyond 13 min (max 12 mph), then only the grade increased by 1% every minute. Oxygen consumption was calculated at 15 second intervals using a computerized system (Parvo Medics True One Metabolic System, Sandy Utah). The system was calibrated with a 3-L syringe and known gases prior to each test. During the test, heart rates, RPE and respiratory exchange ratios were also recorded.

Diet and training

Subjects were given a 3-day food diary to record all food and fluids consumed during the 72 hours prior to each performance run. A copy of the first 3-day diary was given to the subjects and they were encouraged to eat the same or similar items before returning for their second performance run. Each subject was also told to ingest 5 ml of water per kilogram of body weight upon awakening the morning of the performance runs to ensure proper hydration. Subjects were also told to maintain their current training practices and to do similar training the 3 days prior to each performance run.

Performance Run

Upon arrival subjects voided their bladder and were weighed wearing only their shorts on a platform scale (Model BWB-627-A, Tanita Corporation, Japan). The shorts were then weighed so that nude body weight could be calculated. Subjects were then seated for 5 minutes and a blood sample was drawn from a superficial forearm vein using a 21-gauge needle. Blood was then inverted in a heparin vacutainer and immediately spun in a centrifuge for 15 minutes at 3400 RPM. Following centrifugation, plasma osmolality was measured (uOsmette Model

5004, Precision Systems, Natick, MA) to ensure subjects were euhydrated according to ACSM standards [27]. Ten minutes after arriving at the lab, subjects began the hyperhydration phase. Subjects were given either the glycerol containing drink or the placebo. The glycerol drink was a 20% solution of glycerol (NOW Foods, Bloomingdale, IL) in water by weight equal to 1.2 grams glycerol per kilogram of body weight. To mask the sweetness of glycerol, both the glycerol drink and the placebo drink contained 1 gram per 120 ml of artificial sweetener (Equal, Merisant US, Inc., Chicago, IL) and 1 gram per 60 ml of a colored artificial sweetener (Great Value raspberry ice, Wal-Mart Store, Bentonville, AR). At this time subjects swallowed the core temperature pill (VitalSense Integrated Physiological Monitoring System, Mini Mitter) so that the pill had sufficient time to pass into the gastrointestinal tract so it would not be affected by fluid ingestion during the performance run. The hyperhydration phase began 2 hours 20 minutes prior to the beginning of the performance run. Ingestion of the glycerol or placebo solution was completed in 30 minutes after which subjects were given 1 hour 20 minutes to ingest enough water so the entire fluid consumption equaled 26 ml per kilogram of body weight. During the hyperhydration phase subjects remained seated in a thermoneutral environment at 23.5° (0.5°) Celsius and 35% (5%) humidity. Subjects were allowed to get up to urinate as necessary, which was collected and measured. Two hours after entering the lab, subjects finished fluid consumption and urinated if necessary. Post-hydration phase weights were then taken and subject was fitted with a heart rate monitor. At 2 hours and 20 min subjects began a 5 minute warm-up at 60% of VO_{2peak} in an environmental chamber (Tescor, Inc) set at a temperature and humidity of 30° C (1°) and 50% (5%) relative humidity. Following the warm-up, subjects exited the chamber, were towel dried and weighed. At 2 hours and 30 min subjects entered the chamber to begin the performance run.

The performance run consisted of a distance that the subject had to complete as fast as possible. In a study by Schabort et al. (1998), 8 trained distance runners ran a 60 minute time trial on three different occasions and each time averaged a pace that elicited a heart rate equivalent to 80-83% of VO_{2peak} . In order to determine an individual distance for each subject that would take an estimated 60 minutes to complete, the distance was determined by finding the speed that elicited 83% of VO_{2peak} . A fixed workload to exhaustion protocol was abandoned because it was not congruent with the way in which races are run. A set distance was also abandoned due to the possibility of large variations in finishing time and how this may affect levels of dehydration and fatigue, undermining any possible effect of glycerol. Subjects began from a running start equal in speed to the warm-up. They were able to increase or decrease the speed as they saw fit, reminded that they are to complete it as quickly as possible. Subjects were unable to see speed, time or heart rate data, only the distance.

Subjects were given up to 500 ml of water to ingest during the run. Water was at room temperature when ingested to further limit effects on core temperature monitoring. Subjects were handed a bottle of water at each mile and allowed to drink as much as they wanted. These amounts were recorded and replicated on the second performance run. Immediately following completion of the run subjects were towel-dried and weighed. Their shorts were also weighed due to absorbance of sweat so calculation of nude body weight could be determined. Following the weight measurements, subjects sat for 5 minutes and a blood draw was taken for plasma osmolality measurements.

Fluid retention during the hyperhydration phase was calculated as the difference between fluid ingested and urine volume prior to the warm-up. Body mass increase during the hyperhydration phase was also measured as the difference between the post-hydration weight and the initial weight.

Sweat loss was determined by differences in body weight prior to and after the performance run. Corrections were made for the amount of fluid ingested during the run. Dehydration as % weight lost was calculated as the difference between the initial weight and the post-run weight divided by the initial weight. Core temperature and heart rate measures were taken every 5 minutes and at every mile. RPE was measured at every 10 minutes and at every other mile.

Statistics

All statistical calculations were done via computer based statistical software (SPSS ver. 16.0, Chicago, IL). Paired t-tests were performed for all data. Level of significance was set to $p < 0.05$. All values quoted in the text, tables and figure are means (SEM), unless indicated otherwise.

RESULTS

Pre-hyperhydration phase data

Baseline plasma osmolality, initial body weight, and average 3-day fluid intake were not different between trials (Table 3.2), suggesting an equal level of euhydration. Average 3-day caloric intake [glycerol = 2126 (254) kcal, placebo = 2210 (166) kcal] was not different between trials.

Treatment	Plasma osmolality (mOsm·kg ⁻¹)	Initial body weight (kg)	Average 3-day fluid intake (L)
Glycerol	283 (2)	69.1 (4.0)	6.1 (1.5)
Placebo	282 (3)	69.2 (4.0)	6.5 (4.6)

Table 3.2: Baseline measures of hydration. Mean (SEM). P > 0.05 for all values.

Hyperhydration phase data

Urine outputs during the hyperhydration phase were higher in the placebo trial [1402 (273) ml] than in the glycerol trial [817 (176) ml], however they were not significantly different (P = .109). The hyperhydration volume (Fig. 3.2) at the end of the hyperhydration phase was not significantly different between trials. The hyperhydration volume resulted in a weight gain of 833 (157) g for the glycerol trial and 280 (215) g for the placebo trial, also not significantly different (P = .120).

Figure 3.2: Mean hyperhydration volume (ml). Gly = 977 (134) ml, PI = 391 (223) ml. $P > 0.05$.

Prior to starting the run, core temperatures [glycerol = 37.0 (0.2) °C, placebo = 37.1 (0.2) °C] and body weight [glycerol = 69.8 (4.1) kg, placebo = 69.3 (4.0) kg] were not different between trials.

Two of the six subjects experienced nausea or bloating following the glycerol ingestion. These symptoms subsided by mile 2 of the run.

Performance run data

The time to complete the performance run (Fig 3.3) was not different between the two trials ($P > 0.05$). The average time was 4074 (94) s and 4079 (120) s for the glycerol and placebo trials, respectively. There was no order effect for performance between the two trials ($P > 0.05$). Subjects ingested an average of 274 (49) ml of water during the run. Heart rate, RPE and core

temperatures (Fig. 3.4, 3.5, 3.6, respectively) were not different between trials at any given mile interval or at the end of the run. The estimated 1 hour sweat rate was similar between trials (Fig. 3.7). During the glycerol trial subjects lost a lower percentage of initial body weight from sweat loss than they did during the placebo trial (Fig 3.8), although this was not significant. The post-run plasma osmolality was higher in the glycerol trial than the placebo trial [$294 (3) \text{ mOsm} \cdot \text{kg}^{-1}$, $284 (5) \text{ mOsm} \cdot \text{kg}^{-1}$, respectively], but was not significant.

Figure 3.3: Mean time (seconds). $P > 0.05$ at all points.

Figure 3.4: Mean heart rate (beats per minute). $P > 0.05$ at all points. R = Resting, W = Warmup, F= Final.

Figure 3.5: Mean RPE. $P > 0.05$ at all points. R = Resting, W = Warmup, F = Final.

Figure 3.6: Mean Core Temperature (°C). $P > 0.05$ at all points. R = Resting, W = Warmup, F = Final.

Figure 3.7: Mean 1 hour sweat rate ($\text{liter} \cdot \text{hour}^{-1}$). Gly = 1.84 (0.20), Pl = 1.87 (0.20). $P > 0.05$.

Figure 3.8: Mean percent weight loss. Gly = 1.57 (0.28) %, PI = 2.40 (0.36) %. $P > 0.05$.

DISCUSSION

The main finding of this study was that glycerol hyperhydration did not improve endurance running performance in 30°C and 50% humidity. The average time to complete the run was only different by 5 seconds. Marino suggested that subjects that used a self-selected pace protocol may have been able to regulate RPE and thermal strain resulting in no performance difference [16]. However, with dehydration occurring early without glycerol,

cardiovascular and thermoregulatory strain should occur sooner and it would seem that athletes would slow down in an effort to maintain the same exertion, leading to performance differences. This has been verified by Coutts et al. as they saw an overall 2.1% increase in performance with no difference in cardiovascular or thermoregulatory parameters during an Olympic distance triathlon (lasting >2 hours). Coutts et al. attributed the increase in performance to the greater fluid retention and postponement of dehydration with glycerol hyperhydration [15]. Other studies on dehydration and performance have also not seen changes in cardiovascular or thermal strain during the first hour of exercise with similar temperatures and intensities as the current study but have led to better performance [2, 5]. The protocol by Marino [16] and the one used in the current study had athletes only exercising for ~1 hour, possibly limiting the time that 2% dehydration was present and reducing the potential for performance differences.

Subjects that become dehydrated experience increased cardiovascular and thermoregulatory parameters and perception of effort at a given intensity compared to euhydrated subjects [2]. This results in an earlier fatigue, or during self-selected pace protocols, a tendency to maintain perception of effort via slowing down, resulting in similar cardiovascular and thermoregulatory parameters but performance differences [9]. Our hypotheses that glycerol hyperhydration will not alter heart rate, core temperature and RPE were based on these ideas. Because the overall time was not different at any point during the self-selected pace run, the run can be seen as an externally fixed load. Marino has stated that an externally fixed load should have proportional increases in physiological responses [16]. We can now discuss our hypotheses as though differences in the above mentioned parameters should have been different.

Glycerol hyperhydration did not result in a larger fluid retention than water hyperhydration. The hyperhydration protocol was similar to those used in previous studies that had significantly higher fluid retentions and increased performances with glycerol [9, 11]. The hyperhydration volume with glycerol (977 ml), as well as the difference between glycerol and placebo hyperhydration (586 ml), are similar to values reported in previous literature [10, 11, 15, 19, 33]. In light of these similarities, it is difficult to explain the lack of significance for fluid retention. Glycerol is said to be reabsorbed from the distal and proximal tubules in the kidney, producing an osmotic gradient that allows for the reabsorption and retention of water [33]. The trend for higher post-run plasma osmolality in the glycerol trial suggests that glycerol was in higher concentration in the blood, as has been noted by Lyons [7]. It cannot be said for certain whether this higher osmolality was present in the hyperhydration phase to induce water retention because plasma osmolality was not measured during that phase. However, a reasonable assumption can be made that glycerol was in high concentration in the blood because of the similarities with previous studies. Therefore, we believe that the hyperhydration protocol was not a factor in the lack of significance with fluid retention. Baseline hydration status also cannot explain the lack of difference in fluid retention as all subjects reported similar 3-day fluid intakes, weighed the same and had plasma osmolalities that suggested they were euhydrated similarly prior to each trial (Table 3.2). One possible explanation for the lack of significance could be the small number of subjects from which the data was taken and the high variability between individuals, creating a need for larger fluid retention than most studies in order to see significance.

Core temperatures were not different between trials. This suggests that glycerol did not decrease thermal strain. This may have been due to the lack of difference in sweat rate, eliminating differences in evaporative potential. Only Lyons and Marino have shown increases in

sweat rate with glycerol hyperhydration [7, 16]. Both authors suggest glycerol alters the thermoregulatory set point allowing for earlier and more sweating [7, 16], even separately from hyperhydration [16]. The current study does not support that idea.

Fluid intake during the run averaged 274 ml, well below the already small amount of 500 ml that is suggested that runners ingest per hour [29]. This small amount of ingested fluid led to % dehydrations of 1.6 and 2.4, for glycerol and placebo respectively. Although not significantly different, placebo lost greater than 2% of body weight, an amount that should see decreases in performance [2, 5, 26]. When this amount of dehydration occurred is not known, so it is possible that there was insufficient time for it to become a limiting factor.

Heart rates were similar between trials. Glycerol did not alter the cardiovascular strain that occurred during one hour of exercise in the heat. An increase in total body water should attenuate the cardiovascular strain associated with dehydration by prolonging the time before it occurs [2]. There was a trend for higher fluid retention with glycerol, however, dehydration greater than 2% of body weight may not have occurred early enough for differences in cardiovascular strain or performance to become evident. Studies that have seen performance differences have lasted long enough to see differences in dehydration that, although significance is not reported, may play a practical role in reducing strain and maintaining performance [2, 5, 9, 11]. Coutts suggested that the ability of glycerol hyperhydration to prolong the time before hypohydration occurs may be the mechanism for increased performance [15]. It is recommended that in order to see differences in dehydration, cardiovascular strain, and eventually in performance, protocols need to be longer (≥ 1.5 hours) and fluid intake during exercise limited.

RPE was not different at any given point during the run. This is not surprising as heart rate, core temperature and % dehydration were also not different, suggesting similar

cardiovascular and thermal strain during both trials. Wingo is the only one to show differences in thermal strain with glycerol hyperhydration, but was unable to show performance differences due to the 8 minute rest period between 10 mile loops [17].

Two of the six subjects complained of nausea or bloating following glycerol hyperhydration. These symptoms were not felt during the water hyperhydration protocol. Gastrointestinal distress has been reported in previous literature on glycerol hyperhydration [8, 15]. It appears that the response to the high gastric volumes is dependent on the individual. Both subjects reported that the discomfort had passed with the first 2 miles of the run. It is suggested that glycerol hyperhydration be practiced prior to use during competitive events so any modifications can be made to limit stomach discomfort.

One limitation to this study is that subjects were a small cohort of male runners. Caution should be taken when drawing conclusions to the general population or to other types of athletes. The subjects in this study had been training and racing frequently and it is possible that they were able to pace themselves accordingly to obtain very consistent performances.

The environmental conditions in which this study was completed also posts a limitation to the generalization of the data. Differences in cardiovascular and thermoregulatory parameters as well as performance may be dependent on whether exercise is completed in moderate or hot conditions. This study was completed at 30°C and 50% humidity; other temperatures and humidities may result in changes in sweat rate, core temperature, heart rate and dehydration which could vary the effectiveness of glycerol.

Another limitation is that there were only 6 subjects that were able to complete the study. This small number of subjects increases the amount of difference needed to see significance in a variable. This may have led to the lack of significant data presented in this study.

CHAPTER 4

CONCLUSION

In the current study, subjects did not retain more fluid when ingesting glycerol and water than when they simply ingested large amounts of water alone. We were also unable to find a performance difference with glycerol hyperhydration when running for an hour at 30°C and 50% humidity. The time that the subjects took to run the set distance only differed by 5 seconds on average. With the pace being similar between both trials we would expect glycerol hyperhydration to lower the strain of running in the heat. However, glycerol hyperhydration was also unable to reduce heart rate, core temperatures or feelings of exertion, meaning subjects experienced similar strain during each run. Two of six subjects did experience some stomach discomfort for the first couple of miles of the run with glycerol ingestion, so use of glycerol should be practiced prior to use during competitive events.

Although glycerol showed no beneficial effect for running for 1 hour in the heat, it is possible the 2% dehydration did not occur soon enough in the placebo trial to show the effectiveness of glycerol. If the run had been longer, then it is possible that the dehydration differences might have caused increased cardiovascular strain and increased core temperatures. This could have led to reductions in pace and decreased performance. We believe that studies

still need to be done with subjects running for a longer amount of time in hot, race-like conditions, because it is in these conditions that fluid intake is limited and dehydration is most likely to reach performance-lowering levels.

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