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A Meta-Analysis of the Effects of Glycerol-Induced Hyperhydration on Fluid Retention and Endurance Performance

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The authors determined, through a meta-analytic approach, whether glycerol-induced hyperhydration (GIH) enhances fluid retention and increases endurance performance (EP) significantly more than water-induced hyperhydration (WIH). Collectively, studies administered 23.9 ± 2.7 mL of fluid/kg body weight (BW) with 1.1 ± 0.2 g glycerol/kg BW, and hyperhydration was measured 136 ± 15 min after the onset of hyperhydration. Compared with ■ WIH, GIH increased fluid retention by 7.7 ± 2.8 mL/kg BW ($P < 0.01$; pooled effect size [PES]: 1.64 ± 0.80, $P < 0.01$, $N = 14$). The use of GIH was associated with an improvement in EP of 2.62% ± 1.60% ($P = 0.047$; PES: 0.35 ± 0.13, $P = 0.014$, $N = 4$). Unarguably, GIH significantly enhances fluid retention better than WIH. Because of the dearth of data, the effect of GIH on EP must be further investigated before more definitive conclusions can be drawn as to its ergogenic property.

Key Words: overhydration, dehydration, exercise capacity, ergogenic aid, cardiovascular function, thermoregulatory function

On exercise initiation the metabolism increases severalfold to match the increased energy demand of the working muscles. Human beings are relatively inefficient at producing movements—only 25% of the energy produced is directly used for locomotion while the remainder 75% is lost as heat (9). Hence, core temperature increases during exercise (56). To avoid hyperthermia, the body eliminates most of the excess body heat through the production and evaporation of sweat, although convection and radiation might participate to the process to a much lesser extent. The rate of sweat production during exercise depends on a variety of factors such as exercise intensity (85), environmental conditions (85), training state (10), degree of heat acclimatization (14), and clothing worn (87). In temperate (20–25 °C) (4, 18, 29, 30) and hot (>30 °C) (38, 59, 60) ambient conditions sweat rates in

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the range of 1–2 L/h have been observed during moderate- (65–75% of maximal oxygen consumption [VO_{2max}]) and high-intensity (≥80% VO_{2max}) exercises.

To optimize endurance performance (EP) (92), the American College of Sports Medicine (83) and the National Athletic Trainers' Association (13) recommend that athletes keep their fluid losses through sweat, urine, and respiration below 2% of body weight (BW) during exercise. It has been shown, however, that athletes routinely undergo dehydration greater than 2% of BW during prolonged land-based sports such as running (72), cycling (22), and triathlon (72). On the other hand, the American College of Sports Medicine, American Dietetic Association, and Dietitians of Canada (70) advocate that athletes should drink enough fluid during exercise to replace all their fluid losses. This latter perspective, however, is not shared nor encouraged by the International Marathon Medical Directors Association (71), which, rather, recommends that fluid consumption during exercise should not surpass 400–800 mL/h. Accumulating evidence indicates that it is difficult for athletes to attempt to balance fluid intake with fluid losses during exercise and that in certain circumstances it might even jeopardize EP (18, 81). In fact, it has been shown that endurance athletes typically only drink 500 mL of fluid per hour during exercise (72). On the other hand, although some endurance athletes might drink more than the aforementioned amount of fluid, they nevertheless rarely replace more than 50% of the sweat losses induced by water-based (88) and land-based (20, 64, 72, 74) exercises. It is thus quite apparent from the findings that, contrary to what the sports-drink industry would like us to believe, humans were not "designed" to maintain euhydration during exercise and apparently prefer to exercise in a dehydrated rather than euhydrated state.

This phenomenon is paradoxical, however, because exercise-induced dehydration has been shown to impair EP in both a moderate and hot climate in certain but not all exercise conditions. In hot ambient temperatures evidence indicates that a lost of BW ≥1.8% is associated with a decline in EP during cycling (5, 6, 93) and walking and running (65) exercise. In a temperate environment, it appears that the body is less sensitive to the loss of body water and that EP, during running and cycling exercises, will not become impaired before a dehydration level ≥3.2% of BW is reached (3, 4, 18, 56, 57), although 1 study showed that a dehydration level of 1.7% of BW was associated with a decrease in EP during running (25). Hence, evidence suggests that dysfunction significant enough to hinder EP occurs at the cellular and systemic level when body-water loss reaches a particular threshold that differs depending on whether the exercise is being conducted in a hot or moderate climate. Exercise-induced dehydration can contribute to reducing EP by decreasing plasma volume (56), stroke volume (60), cardiac output (60), skin blood flow (60) and sweat rate (28) and increasing heart rate (56), rectal temperature (5), glycogen utilization (37), plasma sodium and osmolality level (6), and perceived exertion (93).

It can be advantageous for athletes to hyperhydrate before exercise when it is anticipated that the amount of fluid intake during exercise will not be adequate to maintain EP. In fact, in this particular circumstance, beginning an exercise while hyperhydrated, as opposed to euhydrated, would delay, attenuate, or offset completely the potential effects of dehydration during exercise. Compared with preexercise euhydration, water-induced hyperhydration (WIH) has been demonstrated to increase sweat rate (63), enhance the efficiency of sweating, the slope of the relationship between core temperature and heat-loss response (35, 36), reduce cardiovascular (32, 63, 67, 68) and thermal (27, 32, 35, 36, 63, 68) stresses, and improve EP (7).

Despite the numerous advantages associated with the use of WIH, the efficacy of this strategy remains somewhat limited. In fact, the functional units of the kidneys—the nephrons—eliminate the excess water ingested quite rapidly, thereby minimizing the time period during which the body can remain in a state of elevated body water (26). For example, it has been shown that after the ingestion of 1600–1700 mL of water within a 30-min period 30–75% of the load is excreted through urine over the next 60 min (26, 38). A more suitable and efficient alternative to WIH consists of drinking the excess amount of fluid in conjunction with a substance called glycerol (80).

Glycerol-induced hyperhydration (GIH) has been shown to substantially enhance fluid retention compared with WIH. Riedesel et al. (79), in 1987, were the first to observe that adding glycerol to the water ingested during hyperhydration significantly and substantially reduced urine production compared with WIH. Many studies since that of Riedesel et al. (79) have been conducted that compared the effectiveness of GIH with that of WIH. No studies have yet attempted, however, to quantify from all published studies the average quantity of fluid retention GIH allows above that provided by WIH or whether the amount of fluid retained with GIH is significantly higher than that of WIH. Therefore, the first aim of the current review was to determine, using a meta-analytic approach, the quantity of additional fluid retention that incorporating glycerol into a hyperhydration solution allows compared with WIH and whether this amount is statistically significant. Obviously, the finding that GIH enhances the body's water-retention capacity more than WIH raises the following practical question for athletes: Can GIH, by its ability to increase and sustain the increase in body water, better maintain fluid homeostasis during exercise and, therefore, enhance EP more than WIH? There are several studies that have looked into the effect of GIH on EP, but the magnitude and significance of the effect of this strategy on EP has never been meta-analyzed. Hence, the second aim of this review was to determine, again via a meta-analytic procedure, whether there is a significant difference between the effect of GIH and WIH on EP.

Methods

Magnitude of the Effects of GIH on Fluid Retention

Location of Articles. To locate the articles of interest—those that compared the effectiveness of GIH and WIH in their ability to increase fluid retention or BW—we performed a thorough search of the scientific literature using the PubMed (which includes the new and old MEDLINE) and SPORTDiscus databases. The MeSH headings that we used were, either alone or in combination, *glycerol hyperhydration, glycerol-induced hyperhydration, glycerol hydration, or glycerol,* and *fluid balance*. The search of literature was limited to English-language citations. We also did a manual search of the reference sections of all articles that were found during the electronic search in addition to those of 2 key published review articles on GIH (47, 80). Unpublished manuscripts in preparation for future submission or that had been already submitted for publication at the time of writing the current article were admissible for revision. In order to locate unpublished manuscripts, we conducted a search of the abstracts that have been published in the May supplement of *Medicine and Science in Sport and Exercise* over the past 10 y. Moreover, we searched the available abstracts presented over the past 9 y at the annual meeting of the American Society of Exercise Physiologists. In the case where an abstract was of interest for the present analysis we contacted the authors to determine whether they had a manuscript in preparation. Because the literature on GIH is relatively small, we feel confident that we were able to locate most of the published studies on the subject so far.

Inclusion Criteria. We considered valid, and therefore the computations were made from, results of studies that met at least all of the following criteria: 1.) The hyperhydration periods had to be conducted under strictly controlled laboratory conditions; 2.) the hyperhydration protocols had to be described in such a way to be easily reproduced by other research teams or single individuals (the exact time points at which the liquids [and glycerol] were administered had to be indicated); 3.) the treatments (GIH and WIH) had to be administered in a randomized (or crossover) manner; 4.) the measure of hyperhydration had to be taken at least 90 min after the onset of hyperhydration, which appears to be the minimal amount of time required to observe the hydration advantage provided by GIH over WIH (34, 38, 76); 5.) with the exception of the presence or absence of glycerol, the composition of the hyperhydration solutions had to be identical (we accepted the placebo solution's containing artificial sugar to disguise the distinctive taste of glycerol on the basis that it was unlikely to alter fluid emptying/absorption or excretion rates through urine); 6.) subjects had to be in a similar hydration state before the hyperhydration trials, as evidenced by similar BW, hemoglobin, hematocrit, urine specific gravity, or plasma osmolality levels among trials; and 7.) the studies were published, in preparation to be submitted, or had been submitted for publication in peer-reviewed journals. Case studies were excluded from the analysis (29, 30). Studies comparing the ability of water and water + glycerol to replace exercise-induced fluid losses after exercise were not considered for the analysis on the basis that the hydration dynamic in such conditions might not be representative of what occurs when fluids are administered in a euhydrated state, and those studies were not intended nor designed to look at the effect of hyperhydration (44, 86).

Coding of Variables. All studies were coded for the following variables: 1.) sample size, 2.) gender, 3.) age, 4.) VO_{2max}, 5.) absolute and relative quantity of glycerol administered, 6.) absolute and relative quantity of fluid administered, 7.) the time the measure of hyperhydration was taken (length of the hyperhydration protocol), 8.) absolute difference in fluid retention between GIH and WIH, 9.) absolute difference in fluid retention between GIH and WIH corrected for BW; 10.) absolute retention of fluid during GIH and WIH, 11.) absolute retention of fluid during GIH and WIH corrected for BW, 12.) percentage of fluid given retained during GIH and WIH, and 13.) changes in plasma sodium levels from before to after the hyperhydration period during WIH and GIH.

Measurement of Fluid Retention. For all but 1 study (1) the effect size (ES) and percentage change in fluid retention observed in each study were calculated from the effect of GIH and WIH on the absolute retention of fluid (increase in body water) or increase in BW they allowed 2–2.5 h after the onset of hyperhydration. In the study of Anderson et al. (1), only the absolute and relative changes in urine output were used to determine the capacity of GIH and WIH to enhance body water. Measurements of the percentage change in fluid retention and ES from urine excretion yield figures that slightly differ from those actually measured using the absolute retention of fluid or increase in BW. Because their data did not change the results, however, they were included in the analysis.

Statistics. In studies that only reported the standard errors of the mean (SEMs), the SEMs were converted to standard deviations (SDs) by multiplying them by the square root of the sample size. Data originally reported in graphical form only were converted to numeric values using a high-performance digital caliper (Mitutoyo, Japan).

The ES can be defined as a unitless measure of the efficacy of GIH centered at zero if the effect of GIH is no different than that of WIH. The ESs were calculated using the following formula: $Mean_{GIH} - mean_{WIH}/SD_{WIH}$ ■ (91). The measured ESs were adjusted to compensate for the bias introduced by small sample sizes (91). The ESs were interpreted according to the suggestions outlined by Cohen (15): <0.20 is a trivial and unsubstantial effect, 0.21–0.49 is a small but substantial effect, 0.50-0.79 is a moderate effect, and >0.80 is a large and substantial effect. The variance of each corrected ES and its inverse were calculated to test for homogeneity. The percentage change in fluid retention between GIH and WIH was computed using the following formula: $ES_{GIH} \times (SD_{WIH}/mean_{GIH}) \times 100$ (16). All calculated ESs and percentage changes in fluid retention were combined, and then the averages were calculated along with the SEM and 95% confidence interval (CI). Results were considered statistically significant when the CI did not include zero.

In an attempt to determine possible factors affecting the capability of GIH to increase fluid retention, we calculated Pearson's product–moment correlation coefficients between certain variables of interest, namely, between the absolute retention of fluid during GIH corrected for BW and the relative quantity of fluid administered, relative quantity of glycerol administered, the time the measure of hyperhydration was made, and VO_{2max}.

The clinical significance of the results was computed using the spreadsheet developed by Hopkins et al. (39). Publication bias was calculated with the equation found in Thomas and Nelson (91).

Results. From the databases, as well as manual searches, we identified 23 manuscripts (1, 2, 17, 24, 26, 29–31, 38, 42, 44, 45, 48–52, 61, 62, 76, 79, 86, 95). Three studies were included in Montner et al.'s article (62), and 2 each in Montner et al.'s (61) and Riedesel et al.'s (79) articles. Five published abstracts (33, 46, 66, 77, 94) were located and read, and 4 of them were retained because it was not yet possible at that stage to reject them based on our inclusion criteria (33, 46, 77, 94). Only 1 research team, however, had a manuscript in preparation that was in the process of being submitted to a peer-reviewed journal (34). Thus, our research yielded a total of 28 completed studies. Of these, 14 met our inclusion criteria (1, 26, 31, 34, 38, 50, 51, 61, 62 [first study], 76, 79). Hence, 14% changes in fluid retention and ESs were computed from 11 manuscripts.

The major reasons for nonacceptance of studies were because they did not meet Criteria 1 (52), 2 (2, 17, 24, 52, 95), 3 (2), 4 (90, 91), or 6 (18, 61 [second study]).

The article of Inder et al. (42) was rejected on the basis that it did not compare WIH with GIH, and that of Koenigsberg et al. (45), because the long-term (1.5–2 d) instead of the acute effects of WIH and GIH were compared.

A total of 99 subjects were represented in the 14 investigations analyzed. The mean sample size of studies was 7.9 ± 2.3 subjects. Men and women represented 76% and 13% of all subjects, respectively. The gender of the remaining 11% of subjects was not reported. The mean age (n = 10 studies), weight (n = 12), and relative VO_{2max} (n = 8 studies) of subjects were 26.3 ± 2.6 y, 71.9 ± 4.6 kg, and 56.3 ± 6.3 $mL \cdot kg^{-1} \cdot min^{-1}$, respectively. Hence, the subjects who were studied could be considered moderately trained.

Collectively, results of studies indicate that researchers administered 23.9 ± 2.7 mL/kg BW of fluid (absolute total of 1703.2 ± 179.2 mL) with (GIH) or without (WIH) 1.1 ± 0.2 g glycerol/kg BW (absolute total of 79.8 ± 11.3 g). On average, the measure of hyperhydration was taken 136 ± 15 min after the onset of hyperhydration.

Table 1 reports the percentage changes in fluid retention and associated ESs observed in all studies included in the analysis. The homogeneity statistic, 20.13, was not significant, $\chi^2(df, 13) = 22.36$, $P > 0.05$, indicating that the ESs are homogeneous and describe the same effect. GIH and WIH enhanced body water by 12.9 ± 4.4 mL/kg BW (53% of the initial load of fluid administered) and 5.2 4.7 mL/kg BW (21% of the initial load of fluid administered), or 919.1 ± 324.3 mL and 371.4 ± 340.8 mL, respectively, which is equivalent to a difference in fluid retention of 7.7 ± 2.8 mL/kg BW (95% CI, 6.1–9.3 mL/kg BW), corresponding to a mean ES of 1.64 ± 0.80 (95% CI, 1.19–2.08). The percentage change in fluid retention from WIH to GIH was 50.1% ± 31.4% (95% CI, 32.4–68.7%).

Table 1 Effect Size and Percentage Change in Fluid Retention Observed in Studies Included in the Analysis

Reference	Effect size	Change in fluid retention (%)
1	0.8	25.0
26	3.0	36.4
31	0.7	23.8
34	1.4	72.6
38	2.8	134.3
50	0.8	24.0
51	2.2	78.7
61	1.2	82.4
62	1.6	46.0
62	1.2	42.0
62	1.9	49.0
76	2.4	31.5
79 (1.5 g glycerol/kg BW)	2.2	35.9
79 (1 g glycerol/kg BW)	0.9	26.0

There were no correlations between the absolute retention of fluid during GIH corrected for BW and the relative quantity of glycerol administered or the time the measure of hyperhydration was taken. A strong relationship was observed, however, between relative fluid retention and the relative amount of fluid administered (r = 0.58, P = 0.03) and VO_{2max} (r = –0.88, P = 0.01).

During WIH (n = 5) natremia decreased from 137.5 ± 1.2 mmol/L (before WIH) to 136.5 ± 0.3 mmol/L (after WIH; 95% CI, –1.2 to 3.08 mmol/L). On the other hand, during GIH (n = 5) natremia decreased from 138.0 ± 0.8 mmol/L (before GIH) to 135.2 ± 0.7 mmol/L (after GIH; 95% CI, 1.7–3.8 mmol/L). These changes in sodium level correspond to differences of 0.7% (95% CI: –0.8% to 2.2%) and 2% (95% CI: 1.3–2.7%) for WIH and GIH, respectively.

Considering that the smallest change in fluid retention provided by GIH compared with WIH that would matter to athletes is 280 mL (4.0 mL/kg BW), which represents half the additional amount of fluid retention that GIH allows over WIH, the present results suggest that the true effect of GIH should be above this threshold 100% of the time.

It was calculated that there would need to be 160 unpublished studies on this topic to reduce the ES of 1.6 to a trivial ES of 0.10.

Studies Showing No Beneficial Effect of GIH on Fluid Retention

There are 3 studies in the literature that showed that the use of GIH provided no hydration advantage compared with the use of WIH (29, 30, 61 [second study]). One of those studies even showed that GIH reduced fluid retention compared with WIH (30).

Magnitude of the Effects of GIH on EP

Location of Articles. In order to locate the articles that compared the effectiveness of GIH and WIH on EP, we used the same methodology as that previously described in the section titled Magnitude of the Effect of GIH on Fluid Retention. In our search for articles in PUBMED and SPORTDiscus databases, however, we combined the term *exercise* with the key words previously used and reported.

Inclusion Criteria. For this analysis, computations were made from results of studies that met all the following criteria: 1.) Both the hyperhydration periods and exercise trials were conducted under strictly controlled laboratory conditions and were 2.) placebo-controlled; 3.) treatments (GIH and WIH) were administered in a randomized (or crossover) and double-blind fashion; 4.) with the exception of the presence of glycerol or not, the composition of the hyperhydration solutions had to be identical (we accepted the placebo solution's containing aspartame to disguise the taste of glycerol on the basis that it was unlikely to alter fluid emptying/absorption or excretion rates; 5.) diet was standardized for at least the 24 h preceding the trials; 6) training was standardized for at least the last 24 h before the trials; 7.) subjects had to be in a similar hydration state before the hyperhydration trials, as evidenced by similar BW, hemoglobin, hematocrit, urine specific gravity, or plasma osmolality levels among trials; 8.) the exercise trials were conducted under the same ambient temperature and began no more than 2 h after the end of the inducement of hyperhydration; and 9.) the studies were published, in preparation for being submitted, or had been submitted for publication in peer-reviewed journals. Case studies were excluded from the analysis (29). For reasons previously explained, studies that examined EP after rehydration with water and water + glycerol in hypohydrated athletes were not included in the analysis (44, 86). Moreover, in an effort to not mix findings, we did not include in the analysis results of a study comparing the effect of GIH and WIH on EP while subjects were wearing chemical protective clothing (49). In fact, during exercise in such conditions, when the thermoregulatory system is unable to compensate for the increase in core temperature, the effect of GIH and WIH on EP might be quite different than when it is possible for individuals to thermoregulate efficiently.

Coding of Variables. All studies were coded for the following variables: sample size, gender, age, VO_{2max}, temperature and humidity, length of the exercise periods, intensity of the exercise periods, and the type of protocol used. Because of the low number of studies included in the analysis, we decided not to perform any correlation tests whose goal would have been to determine the influence of certain factors on EP.

Measurement of EP. Studies included in the analysis tracked EP using tests measuring peak power output achieved during an incremental cycling test (31), the amount of work performed within a given period of time (1, 38), or the time taken to reach exhaustion during a fixed power-output test (61). In the current study EP was taken as the effect of WIH and GIH on total work performed or peak power output. To make comparison possible between studies, we converted the difference in time to exhaustion between GIH and WIH observed in the study of Montner et al. (61) to an effective change in power, as suggested by Hopkins et al. (40). Because of the relationship between power and time to exhaustion, the ES characterizing the change in EP in the study of Montner et al. (61) was computed from the data for times to exhaustion.

Statistics. We used the same statistical methods as those used and described in the section Magnitude of the Effect of GIH on Fluid Retention.

Results. The database search yielded 7 articles (1, 17, 31, 38, 52, 61, 95). The article of Montner et al. (61) describes 2 independent studies, so a total of 8 studies were found. Of these 8 studies, 4 met the inclusion criteria (1, 30, 38, 61 [first study]). The reports included in the analysis, together with their most salient results, are summarized in Table 2. Studies that did not meet the inclusion criteria are also summarized in Table 2 to give a full picture of the state of research in the area of GIH. Two abstracts were found in the May supplement issue of *Medicine and Science in Sport and Exercise* (46, 66). Among these, 1 (66) did not meet our inclusion criteria and the other could not yet be excluded based on the information given in the abstract (46). Thus, the lead researcher was personally contacted to determine whether a manuscript was in preparation, which proved not to be the case. Hence, 4 percentage changes in EP and ESs were calculated from the results of 4 studies (1, 31, 38, 61 [first study]).

Studies were excluded on the basis that they did not meet Criteria 1 (17, 52, 95), 5 (61, 95), 6 (61, 95), 7 (18, 61), and 8 (18).

A total of 31 subjects were represented in the 4 studies. The mean sample size in studies was 7.8 ± 2.4 subjects. Men represented 65% of all subjects. The gender

Table 2 Summary of Studies That Evaluated the Effectiveness of Glycerol-Induced Hyperhydration (GIH) on Endurance Performance (EP)

Reference	Number of subjects, gender, and age	Study design	Glycerol/Fluid dose and absolute amount of fluid retention	Type of exercise and climate	Results (compared with WIH)
Temperate climate					
29	1 man, 27 y	CS, R, DB, PC, FT, DC, HC, TC	1.2 g glycerol/kg BW with 26 mL of fluid/kg BW, WIH 453 mL, GIH 1486 mL	2 h cycling at 65% VO_{2max} followed by a cycling test to exhaustion; 25 °C, 38–42% RH	∅ on HR, SR, PE, or PT; ↓ RT and UVE; ↑ EP
31	6 men, 25.2 ± 1.5 y	R, DB, CO, PC, FT, DC, HC, TC	1.2 g glycerol/kg BW with 26 mL of fluid/kg BW, WIH 558 mL, GIH 829 mL ($P > 0.05$)	2 h cycling at 65% VO_{2max} followed by a cycling test to exhaustion; 25 °C, 38–42% RH	∅ on HR, RT, SR, PE, PT, PPO, or EP; ↓ UVE
61 1st study	11 (gender unknown), 32.5 ± 2.7 y	R, DB, CO, PC, DC, HC, TC	1.2 g glycerol/kg BW with 26 mL of fluid/kg BW, WIH 70 mL, GIH 800 mL ($P < 0.05$)	Cycling to exhaustion at 61% maximal workload; 23.5–24.5 °C, 25–27% RH	∅ on RT, SR, PE, PT, GLU, LAC, FFA, EPI, or RER; ↓ HR; ↑ EP
61 2nd study	5 men 32.6 ± 3.1 y and 2 women 33.0 ± 7.0 y	R, DB, CO, PC	1.2 g glycerol/kg BW with 26 mL of fluid/kg BW, WIH 900 mL, GIH 1000 mL ($P > 0.05$)	Cycling to exhaustion at 61% maximal workload; 23.5–24.5 °C, 25–27% RH	∅ on RT, PE, and PT; ↓ HR; ↑ EP
Hot climate					
1	6 men, 23.3 ± 6.6 y	R, DB, CO, PC, DC, HC, TC	1 g glycerol/kg BW with 20 mL of fluid/kg BW, WIH –60 mL, GIH 316 mL ($P < 0.05$)	90 min cycling at 98% LAC threshold followed by 15-min time trial; 35 °C, 30% RH	∅ on PE, GLU, LAC, GU, PCr, EPI, MT, and VO_2; ↓ HR and RT; ↑ SBF and EP
18	7 men and 3 women, 33.3 ± 2.3 y	FS, R, DB, CO, PC, DC, HC, TC	1.2 g glycerol/kg BW with 25 mL of fluid/kg BW, WIH 640 mL, GIH 1010 mL ($P < 0.05$)	1.5 km swimming + 40 km cycling + 10 km running; hot condition: 30.5 °C, 46% RH – thermoneutral condition: 25.4 °C, 52% RH	∅ on SR and PV during rest and exercise in the temperate condition; ↑ PV during rest in the hot condition; ∅ on PV during exercise in the hot condition; ↑ EP
38	8 men, 27.0 ± 4.2 y	DB, CO, PC, FT, DC, HC, TC	1 g glycerol/kg BW with 22 mL of fluid/kg BW, WIH –200 mL, GIH 400 mL ($P < 0.05$)	1 h cycling: 30 min fixed PO followed by 30 min self-selected PO; 32 °C, 60% RH	∅ on HR, RT, SR, or PV during rest and exercise, PE, PT, TS, GLU, LAC, and VO_2; ↑ EP
52	6 men and 1 women, 21.2 ± 2.4 y	R, DB, CO, PC, FT, DC, TC	1.2 g glycerol/kg BW with 21 mL of fluid/kg BW, WIH 1224 mL, GIH 1342 mL ($P < 0.05$)	60 min cycling time trial interspersed with six 1-min sprints; 34.5 °C, 63% RH	∅ on HR, RT, PE, LAC, GLU, PO, or EP; ↓ PV during exercise; ↑ SR
95	12 men, 24.5 ± 1.1 y	FS, R, DB, CO, PC	1 g glycerol/kg BW with 28 mL of fluid/kg BW, WIH 1126 mL, GIH 1338 mL ($P < 0.05$)	48 km mountain biking on rough terrain; 28 °C	∅ on HR, RT, SR, PE, TS, GLU, LAC, or EP; ↓ PT, DEH, and ESQ

WIH indicates water-induced hyperhydration; R, randomized; DB, double-blind; CO, crossover; PC, placebo controlled; FT, familiarization trial; DC, diet controlled; HC, hydration controlled; TC, training controlled; BW, body weight; HR, heart rate; RT, rectal temperature; SR, sweat rate; PE, perceived exertion; PT, perceived thirst; PPO, \bb\; EP, endurance performance; UVE, urine volume during exercise; CS, case study; GLU, glucose; LAC, lactate; FFA, free fatty acid; EPI, epinephrine; RER, respiratory-exchange ratio; GU, glycogen utilization; PCr, phosphocreatine; MT, muscle temperature; SBF, skin blood flow; FS, field study; PV, plasma volume; PO, power output; TS, thermal sensation; DEH, dehydration; ESQ, environmental-symptoms questionnaire; ∅, no effect; ↑, increased; and ↓, decreased.

of the other 35% was not reported. The mean age of participants was 27.0 ± 4.0 y. All subjects were well trained, as reflected by a mean VO_{2max} of 62.0 ± 2.2 mL·kg BW^{-1}·min^{-1}. Studies were conducted under a mean temperature and humidity level of 29.0 ± 5.4 °C and 39.0% ± 15.2%, respectively. Two studies were conducted in a temperate environment (31, 61), and the 2 others were held under hot temperatures (1, 38). Both studies conducted in the heat showed an ergogenic benefit of GIH, which was the case of only 1 study in the moderate ambient condition (61). We decided to combine the results of studies conducted in a temperate and hot climates on the basis that there are insufficient data to date to indicate that GIH affects EP in a climate-dependent manner. The mean length of the exercise periods was 97.7 ± 29.8 min, and the mean intensity at which these exercises were conducted was 71.8% ± 4.9% of VO_{2max}.

The homogeneity statistic, 0.23, was not significant, $\chi^2(df, 3) = 7.82$, $P < 0.05$. Table 3 reports the percentage changes in EP from WIH to GIH along with the ESs observed in each study. Compared with WIH, GIH increased EP by an average of 2.62% ± 1.60% (95% CI: 0.07–5.17%), which is equivalent to a small but nevertheless substantial ES of 0.35 ± 0.13 (95% CI: 0.14–0.56).

If the smallest worthwhile difference in EP that matters to athletes is 0.5–1.5% (40, 41, 78, 90), the present results suggest that 81–95% of the time the true effect of GIH on EP should be practically important (i.e., greater than the 0.5–1.5% level). We determined that 8 unpublished studies comparing the effect of GIH and WIH on EP would be required to reduce the ES of 0.3 to a trivial ES of 0.10.

Table 3 Effect Size and Percentage Change in Endurance Performance Observed in Studies Included in the Analysis

Reference	Effect size	Change in endurance performance (%)
1	0.4	3.5
31	0.3	1.2
38	0.2	4.4
61	0.5	1.3

Discussion

When the proper literature is carefully reviewed, one finds that the capacity of endurance athletes to perform optimally only starts to decline when dehydration reaches a certain threshold that is quite different depending on the temperature in which the exercise is being conducted. Although dehydration has been shown to alter the homeostasis of several key physiological functions (72), it nevertheless does not appear necessary for optimal EP that all the fluid lost during exercise be completely compensated for when dehydration is kept within certain limits. More precisely, the combined results of studies investigating the effect of exercise-induced dehydration on EP (3–6, 18, 56, 57, 65, 93) indicate that EP is preserved if the loss of body water is kept below 1.8% and 3.2% of BW during exercises held under hot and temperate ambient temperatures, respectively. Note that these findings contrast sharply with the recommendations of the American Dietetic Association and Dietitians of Canada (70), which suggest that athletes should aim to maintain euhydration during exercise in order to maximize EP. More reasonably, the American College of Sports Medicine and National Athletic Trainers' Association suggest that EP can be preserved if fluid losses during exercise are kept within 2% of BW, which fits more with the results to date obtained by studies investigating the effect of dehydration on EP.

To preserve EP individuals need to adjust fluid intake to avoid or delay the moment at which exercise-induced dehydration can become detrimental for EP. Any substantial titration of fluid intake during exercise could prove difficult for athletes, however—studies show that their rate of fluid ingestion is seldom more than 500 mL/h (72), barely sufficient to replace 50% (74) of exercise-induced fluid losses. Hence, if the exercise period is long enough or conducted in hot and humid conditions, which can cause a substantial loss of body water in a small amount of time, dehydration might reach levels known to impede EP. For instance, Noakes (72) has shown that dehydration of ≥2–3% of BW is routinely attained by endurance athletes during exercise. Preexercise hyperhydration might be beneficial for exercise conditions under which it is anticipated that the rate of fluid consumption during exercise will not be sufficient to prevent the deleterious effects dehydration can have on EP. In fact, this hydration strategy would act to avoid, attenuate, or delay the moment at which the loss of BW becomes substantial enough to alter EP, which, in turn, could contribute to maintain or reduce the decline in EP. Our goal in this article was to determine, through a meta-analytic procedure, whether GIH has an effect on fluid-retention capacity and EP that is significantly different from that of WIH.

Based on the obtained results, it appears that the addition of glycerol to the fluid ingested during hyperhydration provides a large and substantial hydration benefit compared with the use of WIH. In fact, it was found that GIH increases fluid retention in a significant manner by an average of 50% over WIH, which was associated with a considerable ES of 1.64. Moreover, it was determined that 100% of the time GIH provided a worthwhile level of hyperhydration compared with WIH. In addition, the test for publication bias indicates that there would have to be a very large number of unpublished studies (N = 160 studies) with trivial ESs to reduce the magnitude of improvement in fluid retention provided by GIH to trivial figures. Because it is unlikely that there would be that many unpublished manuscripts, we can relatively safely say that the observed results are valid.

We are aware of no other orally taken substances that have proven as good as glycerol in increasing and maintaining water retention during hyperhydration. Sodium is the compound that probably comes closest to the effects produced by glycerol on fluid retention. In an as-yet unpublished but well-controlled and -conducted study, Griffin et al. (34) compared the effects of adding glycerol (1.2 g glycerol/kg BW) or sodium (100 mEq/L) to a large amount of fluid (26 mL of water/kg BW) on fluid retention over a 5-h period. At 2.5 h after ingestion, which corresponded to the point of highest fluid retention for both treatments, fluid retention was enhanced by 26% in the glycerol condition compared with the sodium condition. A conventional carbohydrate solution (Gatorade) containing 24 mEq/L of sodium was also compared with the sodium and glycerol treatments. Fluid retention with Gatorade was reduced by 57% and 42% compared with the glycerol and sodium solutions, respectively. It is interesting that the carbohydrate solution provided a fluid retention comparable to that provided by the ingestion of water only. The lack of palatability, however, of high-sodium-containing solutions renders this strategy less appealing for athletes (54).

It is pertinent to explain the physiological mechanism behind the capacity of glycerol in increasing fluid retention. Glycerol's effect has been shown to be ADH and aldosterone independent (26, 58). Rather, glycerol increases fluid retention by having a direct effect on the kidneys (26). In fact, circulating glycerol is filtered by the glomerulus, and its reabsorption across the tubular walls substantially augments the osmolality of the interstitial fluid surrounding the epithelial cells, which, in turn, creates a favorable corticomedullary gradient for the reabsorption of the water ingested in excess during GIH. Glycerol can maintain this gradient, and hence water reabsorption, for an extended period of time because it is metabolized and excreted through urine at a very slow rate (12, 38).

Although they are they exception, some investigations (29, 30, 61 [second study]), 2 case studies (29, 30), and 1 full-scale study (61 [second study]) revealed no hydration benefits of GIH compared with WIH. Goulet et al. (29) and Montner et al. (61) showed that GIH did not significantly enhance fluid retention compared with WIH. Goulet et al. (29) explained their findings by the fact that they administered glycerol in divided doses and over too long a time period (80 min) during the hyperhydration protocol, a combination that likely acted to delay the creation of the optimal osmotic gradient enabling maximal reabsorption of fluid at the kidney level. Montner et al. (61) suggest that the lack of prehyperhydration control with respect to fluid intake, diet, and training might have been responsible for their results. The findings of Goulet et al. (30) are even more striking than those of the 2 previous studies in that they observed that GIH actually reduced fluid retention compared with WIH in a trained triathlete. The authors speculated that WIH decreased urine production significantly more than GIH because the water ingested during WIH was integrated into the body-fluid pools relatively more slowly than that ingested during GIH. Unfortunately, no blood, hormonal, or renal measures were made in this study to support these assumptions. These findings indicate that only on rare occasions could the use of GIH provide no hydration advantage compared with WIH. These observations, therefore, should not deter individuals from using this strategy.

Correlations were made in an attempt to bring some insights on the factors that could influence the ability of GIH to improve fluid retention. We found no relationships between the magnitude of the relative fluid retention during GIH and the relative quantity of glycerol administered or the time the measure of hyperhydration was taken. These correlations must be interpreted bearing in mind that the measure of hyperhydration across all studies was made at 2–2.5 h and that the relative amount of glycerol administered among studies did not vary greatly. Hence, the narrow distribution of data might have masked meaningful relationships between variables. Significant relationships were, however, found between fluid retention and the amount of fluid administered or VO_{2max}. The correlation between fluid retention and the amount of fluid administered was expected and is therefore not surprising. On the other hand, the observation of a strong negative relationship between fluid retention and VO_{2max} was not anticipated. This finding indicates that fit individuals retain less fluid during hyperhydration than less-fit individuals. Athletes with a high degree of physical fitness have blood volumes, as well as total body-water stores, that are much higher than those observed in athletes that are less trained (55, 84). Hence, it is possible that as one becomes more fit fluid excretion through urine during hyperhydration becomes more important because the capacity of the body in storing additional body water becomes more limited.

What could be an optimal GIH strategy? Based on the obtained results, it appears that administering 1.0–1.2 g glycerol/kg BW with 26 mL of fluid/kg BW would maximize fluid retention. The glycerol and water can be taken during a 60- to 90-min period, and exercise should start as early as possible after feelings of stomach bloating have subsided, which should minimize the risks of developing untoward effects during the ensuing exercise.

Results of the present analysis would support the use of GIH in endurance athletes who are looking for ways to improve EP. In fact, both the percentage change in EP (2.62%) and its accompanying ES (0.35) were statistically significant. More to the point, it was observed that 81–95% of the time GIH should be associated with a small but nevertheless practically important improvement in EP if one assumes that the smallest worthwhile enhancement in performance that matters to athletes is on the order of 0.5–1.5% (40, 41, 78, 90). One must take into account, however, that those results are derived from the data set of only 4 studies. Moreover, it was estimated that only 8 unpublished manuscripts with trivial ESs would be required to reduce the ES of 0.35 to a trivial ES of 0.10. Rosenthal (82) has suggested that a 5:1 ratio of null, unpublished studies to each published study should be obtained before the possibility of a negating file-drawer effect can be safely eliminated. Results of the present analysis regarding the effect of GIH on EP must be interpreted with this in mind, because even a few unpublished, negative findings could be enough to nullify the overall effect that was observed. Hence, it is clear that additional studies must be conducted before a valid conclusion as to the effect of GIH on EP can be drawn.

Although our results are derived from a small number of studies, the ES associated with the percentage improvement in EP nevertheless compares favorably with those observed in other studies investigating the effect of dietary supplements or nutritional techniques on performance in humans. Doherty and Smith (19) performed a meta-analysis examining the effects of caffeine on EP and observed an overall ES of 0.41 ($P < 0.05$, $N = 76$). Nissen and Sharp (69) determined an ES of 0.36 ($P < 0.05$, $N = 18$) for the effect of creatine supplementation on skeletal-muscle strength. Likewise, creatine supplementation was associated with significant ESs of 0.24 ($N = 17$), 0.19 ($N = 135$), and 0.20 ($N = 69$) for physical activities relying on the ATP-PCr energy system, anaerobic glycolysis, and oxidative phosphorylation, respectively (8). With respect to anaerobic performance, Matson and Tran (53) observed an ES of 0.44 ($P < 0.05$, $N = 35$) after sodium bicarbonate ingestion. Finally, Erlenbusch et al. (23) compared the effect of high-fat versus high- carbohydrate diets on EP and concluded that ingesting high daily levels of carbohydrate improves EP, with an associated ES of 0.60 ($N = 25$). Unfortunately, they did not indicate whether the ES was significant.

When thinking about hyperhydration a question arises as to whether, in field conditions, the extra fluid needing to be transported by athletes could outweigh the hydration benefit provided by the strategy and, therefore, reduce instead of improve EP. In fact, the extra BW having to be carried by athletes could increase the metabolic cost of exercise, impede speed and acceleration, and decrease the power-to-weight ratio. To the best of our knowledge, whether the GIH-induced increase in BW affects EP has still not been scientifically investigated. Results from a recently published study, however, provide some insight into this question. Ebert et al. (21) evaluated the effect of "functional dehydration" on EP during hill climbing in cyclists. After 2 h of cycling in the heat, when rates of fluid ingestion were either high or low, which incurred dehydration levels of 0.3% and 2.5% of BW, respectively, subjects performed an uphill cycling test to exhaustion. Dehydrated athletes had a reduced time to exhaustion, implying that the hydration benefit was superior to the enhanced power-to-weight ratio provided by dehydration. Because it is recommended that GIH be used for exercise situations in which it is considered a priori by athletes that dehydration might impair EP, it is reasonable to think that the hydration advantage provided by GIH would outweigh the "disadvantage" of the GIH-induced increase in BW, at least during cycling exercise. It is clear, however, that research needs to be conducted evaluating the effect of GIH on EP during weight-bearing activities performed in field conditions or simulated in laboratories to replicate field conditions.

Exercise-induced hyponatremia is a topic that has received a great deal of interest since its very first description in 1985 by Noakes et al. (75). Hyponatremia is defined as a serum sodium concentration of 135 mmol/L or less (89). Symptomatic hyponatremia, described as a clinical condition in which cerebral functions are altered, usually occurs at serum sodium concentrations below 130 mmol/L (89). This condition develops as a result of fluid overloading caused by excessive fluid ingestion (73). Because GIH overloads the fluid compartments, we were interested in determining whether the diluting effect of GIH is sufficient to diminish natremia levels below 135 mmol/L. In the present analysis, it was determined that GIH decreased natremia by 2%, from 138.0 ± 0.8 mmol/L before GIH to 135.2 ± 0.7 mmol/L after GIH. Hence, these results suggest that although GIH decreases serum sodium concentrations, the magnitude of decline is not sufficient to cause hyponatremia.

Conclusion

Research has clearly established that athletes develop dehydration while performing prolonged exercise. It has been demonstrated that dehydration can impair EP under certain exercise circumstances. Inducing hyperhydration before exercise delays, attenuates, or prevents the effects of dehydration during exercise. Therefore, hyperhydration might prove useful in situations in which athletes anticipate that dehydration could impair their performance. Whether GIH has an effect on fluid retention and EP that is significantly different from that of WIH had not yet been addressed using a meta-analytic approach. The results of this review indicate unequivocally that GIH increases BW in a significant manner compared with WIH. More specifically, our data indicate that GIH improves fluid retention by 50% compared with WIH, which is associated with a very large ES of 1.64. On the other hand, results on the effect of GIH on EP indicate that, on average, GIH is associated with an improvement in EP of 2.62% compared with WIH, corresponding to an effect size of 0.35, which is considered small but significant. On the practical side, if the smallest worthwhile increase in EP that is of interest for athletes is 0.5–1.5%, GIH should improve EP above this level 81–95% of the time. Nevertheless, the effect of GIH on EP should be interpreted with great caution, because the results derive from only 4 studies. Hence, until more studies on the topic are conducted it will not be possible to define more clearly the effect of GIH on EP.

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