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REVIEW ARTICLE

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Guidelines for Glycerol Use in Hyperhydration and Rehydration Associated with Exercise

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Contents

Abstract

Dehydration in athletes alters cardiovascular and thermoregulatory function and may inhibit endurance exercise capacity if fluid loss exceeds 2% of body-weight (BW). If this level of dehydration cannot be prevented when starting from a state of euhydration, then athletes may create a state of hyperhydration by consuming extra fluid prior to exercise. From this hyperhydrated situation, individuals have a greater capacity to tolerate fluid loss before becoming dehydrated. Furthermore, excess pre-exercise fluid intake enhances thermo-regulatory ability, as well as increasing plasma volume to maintain cardiac output. However, hyperhydrating before exercise is difficult, because a large fluid intake is typically accompanied by diuresis. Glycerol-containing beverages create an osmotic gradient in the circulation favouring fluid retention, thereby facilitating hyperhydration and protecting against dehydration. Many studies have shown that increases in body water by 1 L or more are achievable through glycerol hyperhydration. This article analyses the evidence for glycerol use in facilitating hyperhydration and rehydration, and provides guidelines for athletes wishing to use this compound. An analysis of the studies in this area indicates that endurance athletes intending to hyperhydrate with glycerol should ingest glycerol 1.2 g/kg BW in 26 mL/kg BW of fluid over a period of 60 minutes, 30 minutes prior to exercise. The effects of glycerol on total body water when used during rehydration are less well defined, due to the limited studies conducted. However, ingesting glycerol 0.125 g/kg BW in a volume equal to 5 mL/kg BW during exercise will delay dehydration, while adding glycerol 1.0 g/kg BW to each 1.5 L of fluid consumed following exercise will accelerate the restoration of plasma volume. Side effects from glycerol ingestion are rare, but include nausea, gastrointestinal discomfort and light-headedness. In summary, glycerol ingestion before, during or following exercise is likely to improve the hydration state of the endurance athlete.

Mechanisms that regulate body water are complex. Fluid intake factors such as volume, temperature and composition of ingested fluid, together with gastrointestinal absorption rate, need to be balanced against fluid loss factors such as sweat and renal excretion rates.[1] These can be extensively influenced by environmental conditions, with heat and humidity significantly increasing the rate of fluid loss and altering the distribution of body fluid to aid in heat dissipation.[1] Fluid losses, or shifts between compartments with dehydration, reduce plasma volume and cardiac stroke volume, with concomitant increases in heart rate.[2-4] Peripheral blood supply may be reduced to maintain central blood pressure, leading to a reduction in heat dissipation and increased core temperature.[5,6] These physiological changes may contribute to exertional heatstroke, which may be fatal.[7-9] Furthermore, endurance performance may be impaired when fluid losses exceed approximately 2% bodyweight (BW) during exercise,[10,11] or when subsequent exercise commences when an athlete is still hypohydrated by 2% BW or greater.[12-16]

Throughout this review, ‘hyperhydration’ is defined as body water excess beyond normal fluctuations and is characterized by a urine-specific gravity under 1.010.[17] ‘Euhydration’ refers to normal body water and ‘hypohydration’ implies body water deficits beyond normal fluctuations (urine specific gravity over 1.023).[18] Furthermore, ‘dehydration’ refers to losing and ‘rehydration’ to gaining body water.

When used predominantly as a preparatory mechanism for subsequent endurance exercise, especially in thermally stressful environments, it is accepted that pre-exercise hyperhydration will delay, prevent or attenuate the effects of dehydration.[19,20] However, ingesting a large bolus of fluid before exercise, even in dehydrated subjects, is typically ineffective at inducing hyperhydration, due to a rapid decrease in antidiuretic hormone (arginine vasopressin), leading to augmented diuresis.[21,22] Therefore, any substance that increases fluid retention before, during or after exercise may have beneficial effects on fluid homeostasis and assist the endurance athlete.

Glycerol is a metabolite released during the breakdown of triglycerides, and is distributed in low concentrations throughout all body cells.[23] Its osmotic properties have generated interest in hydration research where the primary focus has been pre-exercise glycerol hyperhydration. Glycerol ingestion with fluid during exercise has also been investigated as a means of attenuating dehydration, while most recently glycerol has been investigated as an agent to assist rehydration.

Several previous reviews[23,24] have discussed the pharmacokinetics and mechanisms by which glycerol assists in fluid retention and endurance performance.[25] The primary aim of this review is to provide athletes with specific guidelines for the use of glycerol for pre-exercise hyperhydration, or in beverages consumed during exercise (with and without pre-exercise hyperhydration) and during post-exercise recovery. There are a number of factors that need to be considered when formulating guidelines for athletes wishing to explore the use of glycerol in preparation for exercise. These are discussed with reference to previous studies (table I) that have investigated these issues. To more accurately compare and contrast these studies, they were evaluated using a scale that assessed a number of factors associated with the minimization of bias in areas such as subject selection, performance and data analysis (table II). The results of this process are shown in table III, and more emphasis has been placed on studies with less experimental bias when formulating the guidelines.

The scoring system itself was developed using items from a number of extensively evaluated and validated tools[48-51] used to assess the quality of randomized, controlled clinical trials. Items were chosen from those used in the Jadad scoring system,[48] the PEDro scale[49] and the Delphi List,[50] in addition to recommendations contained in the CONSORT statement.[51] Finally, items five and 16 were added because of their perceived importance in studies used to assess exercise performance. It should be noted that the final version of the current scale has yet to be rigorously evaluated and validated on its own merit. From their assessment of construct validity, Jadad et al.[48] indicate that scores of 4/6 and 2/3 on their scales separate the bulk of studies into poor and excellent categories. Based on this, many subsequent studies have used a cut-off of >60% to classify a study as excellent.[52,53] From table III it can be seen that only a few publications contained a high number of important elements. Indeed, only five studies scored >60%, each of which found glycerol hyperhydration to be beneficial.

1. Considerations for Glycerol Use

The following sections discuss factors that are fundamental to the use of glycerol in pre-exercise hyperhydration.

1.1 Glycerol Dose

Riedesel et al.[1] investigated the dose-response relationship for glycerol doses of 0.5, 1.0 or 1.5 g/kg BW. All doses increased water retention; however, the hyperhydration achieved with the 0.5 g/kg glycerol dose was not significantly different from water intake alone. Subsequent analysis supports these findings that glycerol doses higher than 0.5 g/kg BW are required to maximize fluid retention. Robergs and Griffin[23] indicate that a glycerol dose of 1.0–1.5 g/kg BW will be required to elevate plasma glycerol levels to 15 mmol/L. This is the concentration above which blood glycerol levels stabilize, thereby maximizing the osmotic gradient for fluid retention.[23] In the Riedesel et al.[1] study, the level of fluid retention was not further increased following consumption of 1.5 g/kg BW over the 1.0 g/kg BW condition. This disproportion between glycerol dose and fluid retention may have occurred because of the direct relationship between plasma concentration and glycerol catabolism/excretion, which increases glycerol removal from the circulation with higher glycerol doses. Urinary glycerol excretion was doubled and tripled in the 1.5 g/kg condition compared with the 1.0 g/kg condition after 2 and 4 hours, respectively.[1] Consequently, the concentration of glycerol remaining in the body and acting to increase the osmotic gradient to assist in fluid retention was similar between the 1.0 and 1.5 g/kg trials.[1]

The top five scoring studies from the quality analysis used glycerol doses of 1.0[35,40] or 1.2 g/kg BW.[34,36,38] All three studies using a dose of 1.2 g/kg BW had fluid retention levels >1 L after 2 hours, compared with 350–500 mL when 1.0 g/kg BW was used. This represents the volume by which total body water is increased above euhydration, which may then be used to convey thermoregulatory and performance benefits. Therefore 1.2 g/kg BW is the recommended dose, which is slightly higher than the average dose of 1.1 g/kg BW given across all pre-exercise hyperhydration studies.[25]

1.2 Volume of Fluid

The total volume of fluid used in glycerol hyperhydration studies ranges from 20 to 29 mL/kg BW. Goulet et al.[25] conducted a meta-analysis on fluid retention associated with glycerol hyperhydration

Table I. Summary of studies using glycerol in beverages for hyperhydration, during exercise or rehydration

Study, year	Subjects	Treatments	Glycerol dose (g/kg BW)	Fluid vol with glycerol (mL/kg BW)	Mean total fluid vol (mL)	Hydration regimen	Fluid with glycerol	Major findings	Exercise protocol
Glycerol hyperhydration without exercise									
Riedesel et al.,[1] 1987 **Series I**	4 M + 3 F, healthy adults	Glycerol Placebo	0.5	21.4	1412	Initial glycerol bolus at time 0, then fluid consumed over 40 min; no exer	H_2O with 0.1% NaCl	In GIH, ~780 (55%), 850 (60%), 920 mL (65%) of ingested fluid retained after 120 minutes for 0.5, 1.0 and 1.5 g/kg BW, respectively. GIH ↓ urine vol through ↑ plasma osmolality, no effect on plasma vol, little additional hyperhydration with 1.5 g/kg compared with 1.0 g/kg, especially after 2 h	No exercise component
	5 M + 3 F, healthy adults	Glycerol Placebo	1.0	21.4	1412	Initial glycerol bolus at time 0, then fluid consumed over 40 min; no exer	H_2O with 0.1% NaCl		
	4 M + 3 F, healthy adults	Glycerol Placebo	1.5	21.4	1412	Initial glycerol bolus at time 0, then fluid consumed over 40 min; no exer	H_2O with 0.1% NaCl		
Riedesel et al.,[1] 1987 **Series II**	5 M + 5 F, healthy adults	Glycerol Placebo	1.0	25.7	1593	Initial glycerol bolus at time 0, with full fluid vol consumed over 210 min; no exer	H_2O with 0.1% NaCl	Fluid retention ~850 mL (53%) after 120 min. Similar (% fluid retained) to results from 0.5 g/kg glycerol with fluid consumed within 40 min. Indicates little additional benefit from consuming fluid over extended period	No exercise component

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Table I. Contd

Study, year	Subjects	Treatments	Glycerol dose (g/kg BW)	Fluid vol with glycerol (mL/kg BW)	Mean total fluid vol (mL)	Hydration regimen	Fluid with glycerol	Major findings	Exercise protocol
Fruend et al.,[26] 1995	11 M, healthy adults	Glycerol H_2O Control	1.5 g/L TBW (= 0.9)	37.0 mL/kg TBW (= 22.2)	1765	Initial glycerol bolus at time 0, then fluid consumed over 30 min; no exer	H_2O (flavoured)	In GIH, ~1250 mL (70%) and ~1200 mL (68%) of ingested fluid retained after 90 and 120 min. GIH ↓ urine flow rates, ↓ free H_2O clearance rates and ↑ fluid retention (~250 mL at 90 min and ~500 mL at 120 min) vs WIH ($p < 0.05$). ADH rose ($p > 0.05$) with glycerol at the same time urine flow and free H_2O clearances differed, indicating a possible relationship	No exercise component
Melin et al.,[27] 2002 Koulmann et al.,[28] 2000	8 M	Glycerol Control	1.1	21.4	1562	Initial glycerol bolus at time 0, then fluid consumed over 90 min; no exer	Mineral H_2O (0.1% NaCl)	In GIH, ~1200 mL (77%) of ingested fluid retained after 2 h. This half-persisted (~560 mL) a further 90 min later. GIH ↑ plasma osmolality. No effect on renin, aldosterone, ADH or ANP	No exercise component
Pre-exercise glycerol hyperhydration									
Lyons et al.,[20] 1990[a]	4 M + 2 F, healthy adults	Glycerol Placebo 1 (large fluid) Placebo 2 (small fluid)	1.0 initial + 0.1 every h after 2 h	Initial bolus 3.3, 24.7 total in first h, total of 28.4 after 4 h	1729 in 1 h[b] 1988 after 4 h[b]	Initial glycerol bolus at time 0, then fluid consumed over 60 min. Exer began 90 min after final fluid intake. Additional glycerol and fluid each h after 2 h	OJ + H_2O	In GIH, ~1470 mL (85%) and ~1380 mL (80%) of ingested fluid retained after 90 and 150 min vs ~1300 mL (75%) and ~860 mL (50%) in WIH. GIH ↓ urine vol before exercise, no effect on haemoglobin, haematocrit or serum	Treadmill walking at 60% $\dot{V}O_{2max}$, with 5 min rest every 30 min (lab based)

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Table I. Contd

Study, year	Subjects	Treatments	Glycerol dose (g/kg BW)	Fluid vol with glycerol (mL/kg BW)	Mean total fluid vol (mL)	Hydration regimen	Fluid with glycerol	Major findings	Exercise protocol
								electrolyte concentrations. GIH ↑ sweat rates, ↓ rectal temperature during exer	
Meyer et al.,[29] 1995	10 M, non-acc	4% CHO-electrolyte drink with 1% glycerol H_2O 5% CHO-electrolyte drink	Unknown (estimated at 0.125 g/h over 60 h)	26	1742 initial then encouraged to drink 1 L/h over 60 h	Initial glycerol solution consumed over 90 min, then additional glycerol solution and fluid consumption variable over 60 h; exercise variable over 60 h	*Ad libitum* 4% CHO-electrolyte drink with 1% glycerol	H_2O alone appeared to provide adequate hydration during submaximal exer in simulated desert conditions. Glycerol showed a nonsignificant trend to ↑ sweat rates	Treadmill walking: 3 × 40 min protocols at 4.8 km/h daily (carrying army pack weighing ~16.5 kg) [lab based]
Montner et al.,[30] 1996 **Series I**	11, endurance trained	Glycerol H_2O	1.2 (1.0 initial + 0.2 at 60 min) as 20% solution	26	1749	Initial 20% (5 mL/kg BW) glycerol solution consumed over 30 min, then additional glycerol dose at 60 min mark; total fluid ingestion over 90 min; exer began 60 min after final fluid intake	H_2O (aspartame-flavoured)	In GIH, ~800 mL (45%) of ingested fluid retained pre-exer (60 min after final fluid consumption) vs ~70 mL in WIH ($p < 0.05$). Pre-exer urine vol ↓ 666 mL with GIH vs WIH ($p < 0.05$). Glycerol ingestion ↓ heart rate but no effect on rectal temperature. GIH ↑ endurance time ($p < 0.05$) in both Series I and Series II	Cycle to exhaustion at 61% W_{max} (lab based)
Montner et al.,[30] 1996 **Series II**	5 M + 2 F, endurance trained	Glycerol H_2O	1.2 (1.0 initial + 0.2 at 60 min)	26 + 3 every 20 min during exercise	1749 + 605.6 mL/h during exercise	Same pre-exer hyperhydration regimen as for Series I.	H_2O (aspartame-flavoured)	The additional fluid consumed during exer prolonged endurance	Cycle to exhaustion at 61% W_{max} (lab based)

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Table I. Contd

Study, year	Subjects	Treatments	Glycerol dose (g/kg BW)	Fluid vol with glycerol (mL/kg BW)	Mean total fluid vol (mL)	Hydration regimen	Fluid with glycerol	Major findings	Exercise protocol
						Additional fluid (CHO-electrolyte solution) consumed during exer		time in both GIH & WIH trials	
Latzka et al.,[31] 1997	8 M, endurance trained, heat-acc	Euhydration (control) Glycerol Glycerol + rehyd H_2O H_2O + rehyd	~1.0 (1.2 g/kg LBM)	~24.1 (29.1 mL/kg LBM); additional fluid consumed during exer	1862	Initial glycerol bolus at time 0, then fluid consumed over 30 min; exer began 30 min after final fluid intake	H_2O (aspartame-flavoured)	No difference in physiological or thermoregulatory responses between treatments, no difference in total urine vols between GIH & WIH	Treadmill walking at 1.56–1.65 m/s at 4–9% grade (= 45% $\dot{V}O_{2max}$) [lab based]
Latzka et al.,[32] 1998	8 M, endurance trained, heat-acc	Euhydration (control) Glycerol H_2O	~1.0 (1.2 g/kg LBM)	~24.1 (29.1 mL/kg LBM)	1862	Initial glycerol bolus at time 0, then fluid consumed over 30 min; exer began 30 min after final fluid intake	H_2O (aspartame-flavoured)	No differences between GIH and WIH for ↑ total body water. No difference in physiological or thermoregulatory responses between treatments. Glycerol ↑ endurance time 14.5% compared with control (33.8 vs 29.5 min). Both GIH and WIH ↓ heart rate over control	Treadmill walking to exhaustion at 1.56–1.65 m/s at 4–9% grade wearing chemical protective clothing (~55% $\dot{V}O_{2max}$) [lab based]
Hitchins et al.,[33] 1999	8 M, endurance trained, heat-acc	Glycerol Placebo	1.0	22	1628	Glycerol solution consumed over 30 min; exer began 120 min after final fluid intake	Diluted CHO-electrolyte solution	In GIH, ~650 mL (48%) and 500 mL (38%) of ingested fluid retained after 90 and 120 min. GIH ingestion ↑ fluid retention by 250 mL (90 min) and 600 mL	Cycle for 30 min fixed power output, + 30 min self-paced variable power output (lab based)

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Table I. Contd

Study, year	Subjects	Treatments	Glycerol dose (g/kg BW)	Fluid vol with glycerol (mL/kg BW)	Mean total fluid vol (mL)	Hydration regimen	Fluid with glycerol	Major findings	Exercise protocol
								(120 min) vs WIH ($p < 0.05$), ↑ performance by 5% in variable workload phase	
Montner et al.,[34] 1999[a]	4M + 2 F	Glycerol pre- + 5% glucose during exer; Glycerol pre- + 0.5% glycerol, 5% glucose during exer; Glycerol pre- + 1.5% glycerol, 5% glucose during exer; H_2O pre- + 5% glucose during exer	1.2 (1.0 initial + 0.2 at 60 min)	26	1768	Initial glycerol solution consumed over 30 min, then additional glycerol dose at 60 min mark. Total fluid ingestion over 120 min from the start of the glycerol solution intake; exer began immediately after final fluid intake	H_2O	In GIH, ~1000 mL (57%) of ingested fluid retained after 2 h. Fluid retention ↑ with GIH vs WIH (~600 mL; $p < 0.05$), serum osmolality ↑ with glycerol, no effect on ADH. Continued glycerol ingestion during exercise ↑ stroke vol, ↓ heart rate	Semi-recumbent cycling at 44% $\dot{V}O_{2max}$ for 110 min (lab based)
Anderson et al.,[35] 2001	6 M, endurance trained	Glycerol H_2O	1.0	20 + CHO-electrolyte drink during exercise	1440	Glycerol solution consumed over 15 min; exer began 120 min after final fluid intake	Low joule cordial mixed with H_2O	In GIH, ~350 mL (25%) of ingested fluid retained after 2 h. GIH ↓ pre-exercise urine vol vs WIH (~400 mL; $p < 0.05$), ↑ forearm blood flow, ↓ heart rate during exercise, ↓ rectal temperature late in exercise, ↓ skin temperature late in exercise, ↓ ANP, ↑ performance by 5%	Cycle at 98% LT for 90 min, followed by max effort for 15 min (lab based)

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Table I. Contd

Study, year	Subjects	Treatments	Glycerol dose (g/kg BW)	Fluid vol with glycerol (mL/kg BW)	Mean total fluid vol (mL)	Hydration regimen	Fluid with glycerol	Major findings	Exercise protocol
Coutts et al.,[36] 2002	7 M + 3 F, endurance trained	Glycerol Placebo	1.2	25	1955	Glycerol solution consumed over 60 min; exer began 70 min after final fluid intake	Diluted CHO-electrolyte solution	In GIH, ~920 mL (47%) of fluid was retained after 2 h on the warm day and ~1080 mL (55%) on the hot day. GIH ↑ fluid retention 350 mL (↑ plasma vol, ↓ urine) vs WIH ($p < 0.05$). Glycerol reduced the ↑ in completion time between hot and warm conditions for ODT, no difference in sweat rates	ODT (1.5 km swim, 40 km cycle, 10 km run) [field based]
Magal et al.,[37] 2003	11 M, endurance trained	Three phases per trial: (i) hyperhydration with/without glycerol (ii) dehydration (iii) rehyd with/without glycerol	(i) 1.0 (ii) – (iii) 0.5	(i) 22 (iii) 10 (iii) 11	(i) 1703 (iii) 774 (iii) 851	Glycerol solution consumed over 15 min, then fluid consumed over the next 135 min. Exer began immediately after final fluid intake. Additional fluid consumed during exer. During rehyd, glycerol solution consumed over 15 min with total fluid consumption over 90 min	(i) H_2O (flavoured) (ii) CHO-electrolyte solution (iii) H_2O (flavoured)	In GIH, ~1100 mL (65%) of ingested fluid retained after 2.5 h. GIH ↑ fluid retention (↓ urine production by ~900 mL) vs WIH ($p < 0.05$), ↑ plasma vol (~7%), no performance benefits	Specific skill and agility tests followed by 75 min tennis match (field based)

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Table I. Contd

Study, year	Subjects	Treatments	Glycerol dose (g/kg BW)	Fluid vol with glycerol (mL/kg BW)	Mean total fluid vol (mL)	Hydration regimen	Fluid with glycerol	Major findings	Exercise protocol
Marino et al.,[38] 2003	6 M + 1 F, endurance trained	Glycerol Placebo	1.2	21	1655	Glycerol solution consumed over 150 min; exer began immediately after final fluid consumption	Concentrated OJ mixed with H_2O	In GIH, ~1350 mL (82%) of ingested fluid retained after 2.5 h. GIH ↓ urine output (~118 mL) vs WIH ($p < 0.05$), ↑ % change in blood vol after 60 min, ↑ heart rate during high-intensity efforts, ↑ sweat rates. No difference between trials for total distance cycled, rectal temperature, mean skin temperature, power produced, perceived exertion, lactate or glucose	Cycle 60 min with aim to complete greatest distance possible. 1 min sprints at 10, 20, 30, 40, 50, 60 min marks (lab based)
Wingo et al.,[17] 2004	12 M, endurance trained, heat-acc	H_2O + glycerol pre- + H_2O during exer H_2O pre- but not during exer; H_2O pre- + during exer;	1.0	2.8% BW	2153 (+ up to 1200 mL per 10-mile loop (3600 mL total *ad libitum*)[c]	Glycerol solution consumed over 120 min; exer began 35 min after final fluid intake	H_2O (flavoured)	In GIH, ~1350 mL (63%) of ingested fluid retained after 130 min. GIH ↓ pre-exercise urine vol (~200 mL) vs WIH ($p < 0.05$), ↓ post-exer thirst, ↓ dehydration post-exercise, ↓ post-exercise environmental symptoms questionnaire score, ↓ time for final 10 miles by 5 min ($p > 0.05$); heart rate and rectal temperature not altered during exercise	3 × 10 mile loop mountain bike race (8 min break between loops) [field based]

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Table I. Contd

Study, year	Subjects	Treatments	Glycerol dose (g/kg BW)	Fluid vol with glycerol (mL/kg BW)	Mean total fluid vol (mL)	Hydration regimen	Fluid with glycerol	Major findings	Exercise protocol
Goulet et al.,[39] 2006	6 M, endurance trained	Glycerol H_2O	1.2	26 mL/kg BW before exer + 500 mL/h during exer	1781 + 830 during exer	Glycerol and fluid intake over 110 min (glycerol solution given at 0, 40 and 80 min marks, H_2O given at 20 and 60 min marks); exer began 10 min after final fluid consumption	H_2O (aspartame-flavoured)	GIH ↑ TBW ~800 mL (45% of ingested fluid) after 110 min. GIH ↓ urine production by 271 mL pre-exercise (not significant) and 246 mL during exercise ($p < 0.05$) vs WIH. No effect on sweat rate, rectal temperature, perceived exertion, endurance performance (time to exhaustion) or peak power output	Cycle at 65% $\dot{V}O_{2max}$ for 120 min, followed by 5 min break then an incremental cycle to exhaustion (lab based)
Easton et al.,[40] 2007	12 M, endurance trained	Placebo/glycerol Placebo/placebo Creatine/glycerol Creatine/placebo	1.0	~28.6/day[b]	2000 mL[d]	On day of trial, glycerol solution consumed over 60 min, then additional fluid over the next 180 min; further 60 min until exer began[d]	H_2O	GIH ↑ H_2O retention vs WIH by 500 mL in placebo trial & by an additional 240 mL in creatine trial ($p < 0.05$). Glycerol ↓ heart rate, rectal temperature and perceived exertion. No performance benefit	Cycle at 63% W_{max} for 40 min, followed by 16.1 km (10 mile) time trial (lab based)
Nishijima et al.,[41] 2007 Experiment 1	10 M, healthy adults	Glycerol 1 Glycerol 2 Placebo	1.2	25	1651	Placebo and glycerol 1 solution (glycerol mixed in the full vol of fluid) consumed over 60 min. Glycerol 2 was	Diluted CHO-electrolyte solution	In GIH, ~600–800 mL (36–48%) of ingested fluid retained after 3 h. GIH 1 ↓ urine vol by 671 mL vs WIH ($p < 0.05$). GIH 2 ↓ urine vol by 843 mL vs WIH ($p < 0.05$) but GIH 1 & GIH 2 were not	No exer component

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Table I. Contd

Study, year	Subjects	Treatments	Glycerol dose (g/kg BW)	Fluid vol with glycerol (mL/kg BW)	Mean total fluid vol (mL)	Hydration regimen	Fluid with glycerol	Major findings	Exercise protocol
						1.0 g/kg BW glycerol in 8 mL/kg BW fluid bolus within 30 min, then additional fluid over the next 60 min (with additional glycerol 0.2 g/kg BW ingested with fluid 60 min after starting hydration)		significantly different ($p > 0.05$)	
Nishijima et al.,[41] 2007 Experiment 2	6 middle-distance runners	Glycerol Placebo	1.2	25	1651	Placebo solution consumed over 90 min. Glycerol was the glycerol 2 protocol from experiment 1	Diluted CHO-electrolyte solution	In GIH, ~850 mL (51%) of ingested fluid retained after 3 h. GIH ↑ BW by 790 mL vs WIH ($p < 0.05$), and ↑ average power by 9% ($p > 0.05$) vs WIH	Cycle for 40 min fixed power output, + 30 min self-paced variable power output (lab based)
Dini et al.,[42] 2007[a]	14 M, national level oarsmen	Glycerol pre- + H_2O during exer Glycerol pre- + glycerol during exer H_2O pre- + H_2O during exer	1.0 pre- + 1.0 during exer	28.5 pre- + 4.5 during exer	2500 pre- + 400 during exer	Pre-exercise glycerol solution consumed over 90 min, then 180 min until exer began. Additional 2 × 200 mL solutions consumed at ~30 and 60 min marks during exer	H_2O	Following the exercise test, fluid retention ↑ 630 mL in GIH compared with WIH ($p < 0.05$). Glycerol to the rehydration beverages during exercise significantly ↓ fluid loss (~300–525 mL), and improved work capacity at the anaerobic threshold, compared with both of the other hydration regimens	89 min rowing protocol: 6 × 3 min blocks, with 1 min rest between each, starting at 250 W and ↑ to 400 W in 30 W increments; repeated 3 times with 15 min break between each (lab based)

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Table I. Contd

Study, year	Subjects	Treatments	Glycerol dose (g/kg BW)	Fluid vol with glycerol (mL/kg BW)	Mean total fluid vol (mL)	Hydration regimen	Fluid with glycerol	Major findings	Exercise protocol
Goulet et al.,[43] 2008	5 M + 1 F, endurance trained	Glycerol Control (euhydration)	1.2	26 pre- + 12.5 during exer	1776 pre- + 853 during exer	At 0 and 20 min, subjects drank 9 and 6 mL/kg BW fluid, each with 0.6 g/kg BW glycerol, then drank 6 mL/kg BW H_2O at 40 and 60 min marks; further 30 min until exercise	H_2O (aspartame-flavoured)	In GIH, ~1100 mL (62%) of ingested fluid retained 30 min after final fluid consumption. Glycerol ↑ endurance time and peak power and ↓ HR and thirst. No effect on rectal temperature (tended to stay lower with glycerol), sweat rate, thermal stress or RPE	Cycle for 120 min at 65% $\dot{V}O_{2max}$ with 5 × 2 min intervals at 80% $\dot{V}O_{2max}$ performed at 12, 32, 52, 72 and 92 min marks); then incremental test to exhaustion (lab based)
Glycerol consumption during exercise[a]									
Murray et al.,[44] 1991	4 M + 5 F, healthy adults	H_2O 10% glycerol; 6% CHO; 6% CHO + 4% glycerol	~0.94 (1.2 g/kg LBM)	3/kg LBM	647	Glycerol solution consumed over initial 60 min of exer	CHO-electrolyte solution	Glycerol ↓ the % change in plasma vol and ↓ overall mean ratings of perceived thirst but no substantial urine, metabolic, hormonal, cardiovascular or thermoregulatory advantages to the consumption of solutions containing 4% or 10% glycerol during exercise	Cycle at 51.8% $\dot{V}O_{2peak}$ for 90 min (lab based)
Siegler et al.,[45] 2008[e]	10 M, experienced soccer players	Glycerol (5.2% solution) Placebo	~0.7	13.4	1000	500 mL of glycerol or placebo solution consumed within 30 min before training, then a further 500 mL consumed after 30 min of training	CHO-electrolyte solution	Glycerol solution attenuated the drop in plasma vol and BW during the training session. No effect on HR during exercise or fatigue test	Variable intensity training drills followed by intermittent endurance test (field based)

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Table I. Contd

Study, year	Subjects	Treatments	Glycerol dose (g/kg BW)	Fluid vol with glycerol (mL/kg BW)	Mean total fluid vol (mL)	Hydration regimen	Fluid with glycerol	Major findings	Exercise protocol
Glycerol use in rehydration[f]									
Scheett et al.,[46] 2001	8 M, non-acc	Glycerol Placebo	1.0	3% BW (100% fluid lost during dehydration)	2487	Glycerol solution consumed over initial 30 min, then fluid consumed over the next 150 min; exer began immediately after final fluid consumption	1st 30% aspartame-flavoured H_2O, remaining 70% H_2O	Glycerol ingestion ↓ urine production, ↑ plasma vol and BW restoration, better rehyd index with glycerol. Also, ↓ rectal temperature (but no thermoregulatory benefits) and significantly longer exer time to exhaustion (12.6%) with glycerol	Cycle to exhaustion at 50% $\dot{V}O_{2peak}$, cadence 60 rpm (lab based)
Kavouras et al.,[21] 2005	8 M, endurance trained, heat-acc	Glycerol H_2O No fluid	1.0	3% BW (75% of fluid lost during dehydration)	2103	Glycerol solution consumed over initial 15 min, then fluid consumed over the next 80 min; exer began 30 min after final fluid consumption	1st 1/3 (glycerol solution) aspartame-flavoured H_2O, remaining 2/3 was plain H_2O	Plasma vol ↑ more and remained higher with glycerol, cutaneous vascular conductance was ↑ with glycerol but no other thermoregulatory mechanisms. No effect on fluid-regulating hormones with glycerol. Glycerol ingestion significantly ↑ time to exhaustion (18%)	Cycle to exhaustion at 74% $\dot{V}O_{2peak}$, cadence 80–100 rpm (lab based)

a Lyons et al.,[20] Montner et al.[34] and Dini et al.[42] also gave glycerol during exercise following glycerol-induced hyperhydration.

b Assuming average 70 kg subjects.

c The full 1200 mL of fluid was consumed at the end of the loop on only three occasions out of the 72 trials. Average fluid consumed ranged from 693 mL to 842 mL across the trials. Average total fluid consumed was 4458 mL for water trial, 4643 mL for glycerol trial and 2240 mL for no fluid during exercise trial.

d Easton et al.[40] 2 × 500 mL daily of treatment solution for 6 days pre-trial + 500 mL of treatment solution with 2 × 500 mL H_2O on day of trial.

e Siegler et al.[45] also gave 500 mL of glycerol solution before exercise.

f Magal et al.[37] also gave glycerol during rehydration following hyperhydration and dehydration in their three-part study.

ADH = antidiuretic hormone; **ANP** = atrial natriuretic peptide; **BP** = blood pressure; **BW** = bodyweight; **CHO** = carbohydrate; **exer** = exercise; **F** = females; **GIH** = pre-exercise glycerol hyperhydration; **H_2O** = water; **heat-acc** = heat acclimated; **HR** = heart rate; **lab** = laboratory; **LBM** = lean body mass; **LT** = lactic threshold; **M** = males; **non-acc** = non-heat acclimated; **ODT** = Olympic distance triathlon (1.5 km swim, 40 km bicycle, 10 km run); **OJ** = orange juice; **rehyd** = rehydration; **RPE** = rating of perceived exertion; **rpm** = revolutions per minute; **TBW** = total body water; **$\dot{V}O_{2max}$** = maximum oxygen consumption; **vol** = volume; **WIH** = pre-exercise water hyperhydration; **W_{max}** = reported as maximal workload; ↑ indicates increase; ↓ indicates decrease.

Table II. Scale to evaluate original investigations for factors associated with the minimization of bias in selection of subjects, performance and analysis of results[a]

1	A clear description of the inclusion and exclusion criteria was provided	Yes ☐	No/not sure ☐	NA ☐
2.	The trials were randomized	Yes ☐	No/not sure ☐	NA ☐
3.	The method used to generate the random allocation sequence, including details of any restrictions (e.g. blocking, stratification) was described	Yes ☐	No/not sure ☐	NA ☐
4.	Sample size was justified (e.g. by power calculation)	Yes ☐	No/not sure ☐	NA ☐
5.	Attempts were made to control and/or monitor pre-trial conditions (e.g. diet, exercise)	Yes ☐	No/not sure ☐	NA ☐
6.	Design incorporated measures of important baseline variables	Yes ☐	No/not sure ☐	NA ☐
7.	There was blinding of all subjects	Yes ☐	No/not sure ☐	NA ☐
8.	There was blinding of all investigators involved in the trials	Yes ☐	No/not sure ☐	NA ☐
9.	Both the method of blinding and the evaluation of the successfulness of blinding were described	Yes ☐	No/not sure ☐	NA ☐
10.	Details were provided regarding the inability of a subject to complete study requirements	Yes ☐	No/not sure ☐	NA ☐
11.	Statistical methods used to compare groups for primary outcome measure(s),[b] and methods for additional analyses, such as subgroup analyses and adjusted analyses, were described	Yes ☐	No/not sure ☐	NA ☐
12.	Both point measures and measures of variability for the primary outcome measure(s)[a] were provided	Yes ☐	No/not sure ☐	NA ☐
13.	The results of between-group statistical comparisons were reported for the primary outcome measure(s)[b] [e.g. an estimated effect size], and its precision (e.g. 95% CI)	Yes ☐	No/not sure ☐	NA ☐
14.	The method used to assess adverse effects was described	Yes ☐	No/not sure ☐	NA ☐
15.	Reproducibility of the primary outcome measure(s)[b] was reported	Yes ☐	No/not sure ☐	NA ☐
16.	If a performance test was used, a familiarization trial was conducted	Yes ☐	No/not sure ☐	NA ☐

a Scoring: the final percentage score is determined by dividing the number of ‘yes’ scores by total number of applicable items (16 minus the number of NA items).

b If primary outcome measure not stated then key measure used.

NA = not applicable.

and found that a fluid volume of 26 mL/kg BW would maximize fluid retention. The current recommendations will therefore be based upon this volume.

Two other studies have investigated the inclusion of glycerol with common pre-exercise hydration regimens.[45,54] While these are not specifically categorized as pre-exercise hyperhydration studies because of the small total fluid intake, they do provide a practical application for athletes. The first study investigated glycerol (1.0 g/kg BW) consumption with a typical pre-race fluid intake.[54] There were no hydration or performance benefits, most likely due to the smaller total fluid intake (1250 mL) combined with the bulk of the fluid being ingested 4 hours before exercise, allowing considerable time for fluid to be cleared by the kidneys before exercise commenced.[54] However, when consuming 500 mL of a glycerol solution within the 30 minutes preceding a 60-minute training session, and another 500 mL half way through training, Siegler et al.[45] showed that glycerol solutions can attenuate the BW and plasma volume losses during exercise. Thus, if an athlete is unable to tolerate the large volumes of fluid (26 mL/kg BW) and glycerol required to induce pre-exercise hyperhydration, then they may consider consuming smaller volumes of fluid and glycerol closer to the commencement of activity.

1.3 Type of Fluid

Carbohydrate-electrolyte beverages (sports drinks) may provide better hydration potential than water alone during prolonged endurance exercise.[55,56] The major factors affecting the absorptive potential of fluids include: type and concentration of carbohydrate, solution osmolality,

Table III. Evaluation of the studies investigating glycerol use for pre-exercise hyperhydration and for rehydration during and after exercise

Eligibility	Randomization[a,b]	Power calc.	Pre-trial conditions	Baseline measures	Blinding[c,d,e]	Non-completers described	Stats described	Data reporting[f,g]	Adverse effects described	Reproducibility reported	Familiarization performance test	% score	Reference
Pre-exercise hyperhydration													
1	1[a]	0	0	1	0	NA	0	2[f,g]	0	0	NA	29	1
0	1[a]	0	0	1	0	NA	1	2[f,g]	0	0	NA	36	20
0	1[a]	0	0	1	1[c]	1	1	2[f,g]	0	0	1	50	29
0	0	0	1	1	2[c,d]	NA	1	2[f,g]	0	1	NA	57	26
0	0	0	1	0	0	NA	1	2[f,g]	0	0	NA	29	47
0	0	0	1	0	1[c]	NA	1	2[f,g]	0	0	NA	36	47
0	1[a]	0	1	1	2[c,d]	NA	1	1[f]	0	0	0	47	30
0	1[a]	0	1	1	2[c,d]	NA	1	1[f]	0	0	0	47	30
0	1[a]	0	1	1	2[c,d]	1	1	2[f,g]	0	0	0	56	31
1	1[a]	0	1	1	2[c,d]	NA	1	2[f,g]	0	0	0	60	32
0	1[a]	1	1	0	2[c,d]	NA	1	2[f,g]	0	1	NA	64	34
0	0	0	1	1	2[c,d]	NA	1	2[f,g]	0	0	1	53	33
0	2[a,b]	0	1	1	3[c,d,e]	NA	1	2[f,g]	1	0	0	73	35
0	1[a]	0	1	1	2[c,d]	NA	1	2[f,g]	1	0	1	67	36
0	1[a]	0	1	0	0	NA	1	2[f,g]	0	0	NA	36	27
0	1[a]	0	1	1	3[c,d,e]	NA	1	2[f,g]	0	1	1	73	38
0	1[a]	0	1	1	2[c,d]	NA	1	2[f,g]	0	0	1	60	37
0	1[a]	0	0	1	2[c,d]	NA	1	2[f,g]	0	0	0	47	17
0	1[a]	0	1	1	2[c,d]	NA	1	2[f,g]	1	0	0	60	39
1	1[a]	0	1	1	3[c,d,e]	1	1	2[f,g]	0	1	1	81	40
0	1[a]	0	1	1	2[c,d]	0	1	2[f,g]	0	0	0	50	41
0	1[a]	0	1	0	0	NA	1	2[f,g]	0	0	0	33	42
0	1[a]	0	1	1	0	NA	1	2[f,g]	1	1	0	57	43
Glycerol during exercise													
0	0	0	1	1	1[c]	NA	1	2[f,g]	1	0	1	53	44
0	1[a]	0	1	1	2[c,d]	NA	1	2[f,g]	0	0	1	60	45

Continued next page

Table III. Contd

Eligibility	Randomization[a,b]	Power calc.	Pre-trial conditions	Baseline measures	Blinding[c,d,e]	Non-completers described	Stats described	Data reporting[f,g]	Adverse effects described	Reproducibility reported	Familiarization performance test	% score	Reference
Glycerol during rehydration													
0	1[a]	0	1	1	2[c,d]	NA	1	2[f,g]	0	0	0	53	46
1	1[a]	0	1	1	2[c,d]	NA	1	2[f,g]	0	0	0	60	21

Scoring: Each column, except the randomization, blinding and data reporting columns, have a maximum score of 1 point. The randomization column has a maximum score of 2 points as it combines items 2 and 3 from table II. The blinding column has a maximum score of 3 points as it combines items 7, 8 and 9 from table II. The data reporting column has a maximum score of 2 points as it combines items 12 and 13 from table II. The following denotes which specific criteria were fulfilled for the columns combining more than 1 item:

a Randomization (item 2).

b Randomization described (item 3).

c Blinding of subjects (item 7).

d Blinding of investigators (item 8).

e Blinding described (item 9).

f Reporting point measures (item 12).

g Reporting group comparisons (item 13).

calc. = calculation; **NA** = not applicable; **stats** = statistics.

pH, electrolyte concentration, volume of fluid and palatability (flavour, temperature, colour).[56] Given that glycerol alters the osmolality and caloric density of solutions it is dissolved in, it is also pertinent to understand the effect it will have on fluid absorption.

Two studies have demonstrated that glycerol may provide a pro-absorptive effect, evidenced through enhanced intestinal water and sodium absorption in rat intestinal perfusion models.[57,58] Wapnir et al.[58] found that glycerol solutions attenuated water secretion into the perfused segment of the small intestine and significantly reduced the outflow of sodium into the lumen, when compared with sports drinks without glycerol. Furthermore, glycerol solutions had a higher influx-to-efflux ratio resulting in a net influx of water (from the intestinal lumen to the circulation), while glucose solutions had a lower influx-to-efflux ratio resulting in a net efflux of water (into the intestinal lumen).[58] Allan et al.[57] tested the absorption of oral rehydration solutions containing 0.75 mmol/L sodium and the following combinations of glucose : glycerol: 75 : 0, 50 : 25, 37.5 : 37.5, 25 : 50, 10 : 65 and 0 : 75 (mmol/L). Substituting glycerol for glucose enhanced both net sodium and water absorption in rat perfusion models, with peak absorption of both sodium and water occurring with the glucose : glycerol ratio of 25 : 50. Thus, the combination of glycerol and glucose enhanced absorption of fluid from the intestinal lumen to the circulation compared with the solution containing glycerol without glucose, and vice versa.[57] While further investigation in humans is required, the similarity of the physiological process associated with sodium and water movement from the intestinal lumen in rats and humans suggests that the results from these trials can be applied to humans with some confidence,[58] although a published abstract indicates that this may not be the case.[59]

In addition, the inclusion of sodium in sports drinks might improve gastrointestinal glucose and fluid absorption,[56] and offer some protection against hyponatraemia. Hyponatraemia typically results from over-hydration with hypotonic fluids during exercise (i.e. drinking water and losing sodium in the sweat).[60-63] The risk of hyponatraemia is very high when so much fluid is consumed that weight gain during exercise exceeds 2.5% BW.[63,64] It has been advocated that drinking sports drinks containing high levels of sodium during prolonged (>2 hours) exercise may help to stabilize the sodium content of the extracellular fluid and assist in the prevention of hyponatraemia.[65-67]

One proposed negative effect of drinking sports drinks prior to exercise is the possible development of hypoglycaemia. However, a recent series of experiments showed that glucose (75 g) consumed 45 minutes prior to exercise resulted in the stabilization of plasma glucose at a level that was not considered hypoglycaemic and was unaffected by exercise intensity.[68] Subsequent trials showed that rebound hypoglycaemia was (i) more evident following glucose ingestion when compared with carbohydrates with a lower glycaemic index;[69] (ii) equally evident following glucose doses of 25, 75 and 200 g;[70] and (iii) more evident when glucose was consumed longer before exercise (75 > 45 > 15 minutes).[71] However, in all of these conditions, hypoglycaemia was only present for the initial 10–20 minutes during steady-state exercise and had no negative effects on subsequent time trial performance lasting approximately 40 minutes.[69-71] Hargreaves et al.[72] have stated that if ingesting carbohydrate pre-exercise, then a reasonable amount (100 g) should be consumed to provide a supply of glucose later in exercise to offset the suppression of fat oxidation.

Most glycerol hyperhydration studies have used aspartame-flavoured water as the hyperhydrating beverage and have consistently induced hyperhydration. Given the rationale that carbohydrate-electrolyte drinks may provide a better hydration potential than water alone, as well as providing sodium to attenuate hyponatraemia, it could also be proposed that consuming carbohydrate-electrolyte beverages with glycerol could further enhance the hyperhydration benefits of glycerol.

1.4 Timing of Fluid with Glycerol

Two different fluid ingestion protocols are used to promote pre-exercise hyperhydration. The first involves quickly ingesting a small concentrated bolus of glycerol solution, then consuming the remaining fluid over a longer duration. The second involves mixing the glycerol within the full volume of fluid, thereby ingesting glycerol with fluid throughout the pre-exercise hyperhydration period. Study methodologies differ greatly in the duration over which these fluids are provided, making it difficult to determine the optimal protocol for fluid consumption relative to glycerol intake. Table I provides details of different protocols used.

One study investigated the difference between these styles of fluid and glycerol delivery and found that the change in bodyweight and urine volume were similar with either mode.[41] However, the results might be confounded by the fact that the duration over which fluids were consumed was longer in the glycerol bolus trial (90 vs 60 minutes).[41] Thus, the optimal period for fluid consumption in relation to the glycerol bolus intake also needs to be considered. The second protocol used in the abovementioned study by Riedesel et al.[1] provided the glycerol bolus that was optimal in the first series of trials (1.0 g/kg BW), with a larger volume of fluid (25.7 mL/kg BW of 0.1% NaCl solution) over a longer duration (3.5-hour period). This fluid regimen reduced hyperhydration to a level similar to the ingestion of 0.5 g/kg BW of glycerol and fluid within 40 minutes (21.4 mL/kg BW of 0.1% NaCl solution) used in the first protocol. However, others have used similar methods with much greater success.[28,37]

Mixing the glycerol through the entire hyperhydration beverage in order to spread the glycerol consumption over a longer period also results in fluid retention.[17,38,41] However, these longer protocols tend to measure hyperhydration immediately after fluid ingestion is completed, while the shorter fluid intakes tend to measure hyperhydration after lengthy equilibration periods. It is not surprising that the percentage of fluid retained is higher if you measure immediately after fluid consumption. Of the five studies scoring highest in the quality assessment, glycerol and fluid were given over 15,[35] 60,[36] 120,[34] 150[38] or 300 minutes.[40] Fluid retention was greatest when glycerol and fluid was ingested over 60–150 minutes.

Noakes et al.[73] highlighted the importance of gastric volume in regulating gastric emptying. Briefly, the maximum rate at which fluid can be delivered from the stomach is significantly influenced by the volume of fluid in the stomach, and therefore by the rate of fluid consumption.[73] The data from Noakes et al. indicate that the rate of water delivery from a 7% carbohydrate solution will be approximately 400 mL per 10 minutes if a gastric volume of approximately 800 mL is maintained.[73] Therefore, an individual should aim to consume 600–800 mL within about 10 minutes of starting the hydration period, and then a further 400 mL each 10- to 15-minute period during the next 50 minutes. This will result in a volume of fluid equal to 26 mL/kg BW (approximately 1820 mL for a 70 kg individual) being consumed within 60 minutes and absorbed within approximately 90 minutes from the onset of fluid intake. If an individual is unable to stomach volumes of this magnitude, then a smaller volume of fluid should be consumed in each 10-minute period, focusing on drinking the fluid as rapidly as possible.

1.5 Duration of Hyperhydration

Glycerol ingestion has been associated with hyperhydration for periods of up to 4 hours.[1,17,20,26,30,33,35-38,74] Peak hyperhydration is determined by the relationship between glycerol and fluid absorption, and clearance. It is difficult to determine when peak hyperhydration occurs, because the timing of measurements of fluid retention varies greatly between studies. Several studies have mapped fluid retention for periods of up to 3 hours after ingestion, without the confounding of an exercise protocol beginning within this period. After 2 and 3 hours, 60–80%[1,20,26] and 45–60%,[1,20,26] respectively, of the ingested fluid was still retained in the glycerol trial (compared with 40–60% and 10–30%, respectively, in the water hyperhydration trial).[26]

Because the absorption of a large volume of fluid will occur rapidly when fluid intake is rapid (as discussed in section 1.4),[73] exercise should commence 30 minutes after final fluid consumption. Waiting for an extended period will result in unnecessary water loss and reduce overall hyperhydration. Waiting 30 minutes after fluid intake should allow sufficient time for the sensation of stomach fullness to subside, while ensuring that exercise begins when hyperhydration is close to maximal.

It has been demonstrated that it is possible to maintain hyperhydration using glycerol for up to 49 hours.[47] For prolonged hyperhydration, water needs to be consumed at either the same or a greater rate than it is lost. Glycerol may assist in this process by decreasing water loss. However, during this time, glycerol would also need to be ingested at rates in excess of its rate of catabolism/excretion. Although the study by Koenigsberg et al.[47] has demonstrated prolonged hyperhydration with glycerol, until further research into sustained hyperhydration (i.e. >4 hours) is completed, the authors would strongly advise against this practice, as it will theoretically increase the risk of hyponatraemia. Whether this could be overcome by using a carbohydrate-electrolyte beverage has not been studied (see section 4).

1.6 Guidelines for Pre-Exercise Glycerol Hyperhydration

Pre-exercise glycerol hyperhydration will be most advantageous when sweat losses cannot be replaced during exercise. However, if euhydration can be maintained during exercise, then pre-exercise hyperhydration may not provide any additional advantage. If an athlete commences exercise in a hyperhydrated state, they must ensure that they do not over-drink during exercise. The additional fluid retained with pre-exercise hyperhydration will act to dilute plasma sodium before commencing exercise. If additional large volumes of hypotonic fluid are consumed during exercise, there exists an increase in the potential risk of dilutional hyponatraemia.[18] Given the hypotonic composition of sweat, the extra fluid stored with pre-exercise hyperhydration may be lost during exercise without a concomitant increase in the loss of sodium, assuming that aggressive fluid intakes are not made during exercise. In addition,

Table IV. Guidelines for glycerol and fluid ingestion to promote pre-exercise glycerol hyperhydration

Only undertake a pre-exercise glycerol hyperhydration protocol if the exercise is likely to induce a reduction in bodyweight (BW) >2%
Consume a glycerol dose of 1.2 g/kg BW with a volume of fluid equal to 26 mL/kg BW. If this volume is too high for an individual, then consider personalizing the protocol by consuming a smaller volume of fluid and glycerol closer to the commencement of activity
Consume the glycerol solution over a period of 60 min
Use the normal choice of beverage. Carbohydrate-electrolyte beverages with a relatively high sodium content might provide an additional advantage, however this requires further investigation
Commence exercise approximately 30 min after the total hyperhydration fluid volume has been consumed
Consider the increased metabolic cost associated with undertaking weight-bearing exercise with elevated BW

the increased chance of having to void during competition should be considered.[18]

From the preceding sections, guidelines for glycerol and fluid ingestion to establish pre-exercise hyperhydration have been formulated and are presented in table IV.

2. Glycerol Ingestion during Exercise

The goal of ingesting fluid during exercise should be to replace enough of the fluid lost as sweat to avoid incurring a fluid deficit of >2% BW and/or an electrolyte imbalance that may lead to hyponatraemia.[18] The volume of fluid to be consumed will therefore depend on the sweat rate during the activity. This is determined by the mode and intensity of exercise, the environmental conditions, exercise duration and individual variation.[18] However, guidelines for glycerol consumption during exercise will also depend upon whether the athlete has hyperhydrated pre-exercise, as this will delay the body water deficit reaching 2% BW. The following sections discuss the use of glycerol during exercise based on whether pre-exercise hyperhydration has taken place.

2.1 Glycerol Ingestion during Exercise, after Pre-Exercise Hyperhydration

Glycerol pharmacokinetics indicate that only small additional doses during exercise are needed to maintain elevated plasma glycerol levels for several hours, when pre-exercise hyperhydration has been undertaken. For example, when a glycerol dose of 1.2 g/kg BW is used to hyperhydrate pre-exercise, plasma glycerol levels should be elevated to saturation kinetics for around 3 hours.[75] Glycerol will then be half eliminated approximately 140 minutes later,[23,75] although this will be more rapid if exercise begins 30 minutes after fluid ingestion, due to increased metabolism.

Three studies have investigated glycerol consumption with fluid during exercise following pre-exercise glycerol hyperhydration (table I).[20,34,42] Montner et al.[34] required subjects to ingest a total of 1.2 g/kg BW of glycerol with water (26 mL/kg BW) pre-exercise in three hyperhydration trials. Subjects ingested a further 5 mL/kg BW every 20 minutes (total 25 mL/kg BW) of solutions containing either (by volume) 5% glucose, 0.5% glycerol (0.125 g/kg BW) in 5% glucose, or 1.5% glycerol (0.375 g/kg BW) in 5% glucose, during 110 minutes of semi-recumbent cycling. While the maintenance of bodyweight during exercise with continual glycerol ingestion was slightly better than with glycerol hyperhydration alone, the benefit was not significant. However, glycerol ingestion during exercise did result in an increased stroke volume and decreased heart rate, indicating improved cardiovascular performance. In support of the above pharmacokinetic data, there was no difference between the 0.5% and 1.5% (0.125 or 0.375 g/kg BW) glycerol solutions.[34] Dini et al.[42] showed that the addition of glycerol to rehydration beverages during exercise significantly increased fluid retention (~525 mL) and improved work capacity at the anaerobic threshold, compared with other hydration regimens. In the Lyons et al.[20] study, the effect of glycerol ingestion during exercise is difficult to establish as no trial existed in which subjects were given glycerol before but not during exercise. Furthermore, no blood samples were taken between the hyperhydration period and the commencement of exercise, so it is impossible to distinguish between the effects of the pre-exercise glycerol bolus and the doses given during exercise.

It is recommended that athletes only consume glycerol during exercise if they are going to incur a fluid deficit >2% BW. A 70 kg athlete (with a total body water volume ~42 L) can lose ~1.4 L of fluid (so that total body water would drop to 40.6 L) in order to reach the 'dehydration threshold' of a 2% reduction in BW. However, the extra fluid retained with hyperhydration is also available to be lost as sweat, thereby delaying the progression of dehydration. If the same 70 kg athlete hyperhydrated pre-exercise by ~900 mL (the average volume retained with pre-exercise glycerol hyperhydration for a 70 kg athlete[25]), then their total body water would increase to approximately 42.9 L. This additional fluid is also available to be lost as sweat before they reach their 'dehydration threshold' of a reduction in total body water to 40.6 L. Now the athlete can lose ~2.3 L of fluid (1.4 L + the additional 0.9 L stored through hyperhydration) before reaching the same relative level of dehydration compared with when they are normally euhydrated. Based on a sweat rate of 1.5 L/h, exercise durations of approximately 90 minutes would be needed to achieve this fluid deficit.

For continued glycerol ingestion with fluid during exercise following pre-exercise hyperhydration, it is recommended the athlete consume a small amount of glycerol (0.125 g/kg BW) in a volume equal to 5 mL/kg BW when exercise is of sufficient duration to dehydrate them by >2% BW. The specific dose is based on the Montner et al.[34] study, as it scored highly (64%) on the scale of research quality compared with the Dini et al.[42] study (33%). Furthermore, it is imperative that athletes avoid drinking any more fluid than a volume that is sufficient to replace sweat loss, so there is no net weight gain during exercise. Thus, if athletes have hyperhydrated pre-exercise, and exercise duration is ≤75 minutes, then very little fluid would be needed during exercise, and the consumption of glycerol with any fluid is not recommended. The American College of Sports Medicine's (ACSM) position stand on fluid replacement also advocates the consumption of beverages containing sodium and/or salted snacks to help stimulate thirst and retain fluids.[18] Carbohydrate in rehydration solutions, while not further facilitating rehydration, may slightly improve the intestinal uptake of sodium and water.[76] Replacement of electrolytes, particularly sodium, is crucial and the inclusion of electrolytes in ingested fluids will help maintain plasma volume.[44,45]

2.2 Glycerol Ingestion during Exercise, without Pre-Exercise Hyperhydration

Athletes starting exercise in a normal euhydrated condition might also benefit from adding glycerol to fluid consumed during exercise, as a means to prevent or delay dehydration by enhancing retention of the ingested fluid. Murray and colleagues[44] are, to our knowledge, the only group to study the specific effects of glycerol on hydration during exercise without any pre-exercise glycerol and fluid ingestion. Siegler et al.[45] gave 500 mL 30 minutes pre-exercise and a further 500 mL during exercise. The small total volume of fluid consumed (647[44] to 1000 mL[45]) in each of these protocols prohibits them being described as hyperhydration studies. Between them, they provided solutions with glycerol concentrations ranging from 4% to 10% of the fluid volume (4% glycerol with 6% carbohydrate and 10% glycerol;[44] and 5.2% glycerol with 4% carbohydrate[45]). The resulting glycerol doses were 0.38 and 0.94 g/kg BW for the 4% and 10% solutions of Murray et al.[44] and 0.7 g/kg BW for the 5.2% beverage of Siegler et al.,[45] respectively.

Over 90 minutes of cycling at 50% $\dot{V}O_2$ peak (in 30°C, 45% relative humidity environment), both the 4% and 10% glycerol solutions reduced thirst sensation and attenuated the decrease in plasma volume seen with the water placebo and sports drink solutions.[44] From 60 to 80 minutes during exercise the 10% glycerol solution provided better maintenance of plasma volume than did the 4% solution; however, they were similar at all other timepoints. The protocol of Siegler et al.[45] resulted in a 40% reduction in BW loss with the glycerol solution. This reflects equal or improved thermal tolerance in the glycerol trials with less dehydration, as no difference was observed between trials for variables such as core temperature and heart rate. Siegler et al.[45] also showed a 55% reduction in the change in plasma volume over 60 minutes of exercise compared with the sports drink. Thus, the addition of glycerol to beverages consumed during exercise has the potential to maintain fluid balance to a greater extent than sports drinks or water alone.

Guidelines for glycerol use during exercise need to consider the duration of the event. Glycerol metabolism is relatively slow (~8–9 g/h).[77,78] No studies have investigated the continual ingestion of glycerol during longer (e.g. ultra-endurance) events. However, because glycerol is slowly metabolized, it may be expected that continual administration over prolonged periods (e.g. >4 hours) will lead to an accumulation of glycerol in the circulation resulting in multiple side effects, some of which may be health threatening.[44,45] Therefore, we recommend athletes consume glycerol 0.4 g/kg BW with fluid during each of the first 4 hours of exercise. This would provide a similar dose to that recommended during hyperhydration, with adjustment for increased metabolism with exercise. After this time, individuals should consume fluid alone where necessary. The volume consumed each hour will depend on sweat rate, exercise duration and opportunities to drink.[18,79] For an event such as the marathon, the ACSM recommend that smaller persons exercising at a lower intensity in cooler environments need to replace around 0.4 L/h, and this is increased to 0.8 L/h for heavier individuals exercising at higher intensities in warmer environments.[18] Finally, similar to all guidelines presented here, glycerol use should only be considered when dehydration is likely to exceed 2% BW. Thus, using the example of the 70 kg athlete starting exercise in a normal euhydrated condition (i.e. who hasn't hyperhydrated pre-exercise), glycerol use is recommended if fluid losses are likely to exceed 1.4 L. Based on a sweat rate of 1.5 L/h, an exercise duration of approximately 60 minutes would be required to achieve this fluid deficit.

2.3 Guidelines for Glycerol Ingestion during Exercise

Guidelines for glycerol ingestion will depend on the extent of dehydration during the activity. Because sweat rates are highly variable, athletes should estimate their sweat rate in conditions similar to those in which performance will take place, to assist in determining a hydration protocol. To do this, weight loss during a session mimicking typical performance should be monitored and corrected for fluid intake, then divided by the duration of the activity. For simplicity, 1 kg weight loss is considered equal to approximately 1 L of fluid. Glycerol use during exercise is then advocated by following the guidelines in table V.

3. Glycerol as a Rehydrating Agent

To date, only three studies have explored the role of glycerol in rehydration (table I).[21,37,46] Most recently, Scheett et al.[46] and Kavouras et al.[21] dehydrated subjects via exercise (by –3% and –4% BW, respectively) before rehydrating (3% BW each) with or without glycerol (1 g/kg BW). The third study to investigate glycerol consumption with rehydration fluid was conducted by Magal et al.,[37] employing a protocol that had three stages: (i) hyperhydration with or without glycerol; (ii) exercise-induced dehydration; and (iii) rehydration with or without glycerol (0.5 g/kg BW).

Table V. Guidelines for the inclusion of glycerol in rehydration fluids given during exercise

Glycerol use should be considered when exercise is of sufficient duration to dehydrate by >2% bodyweight (BW)
If pre-exercise hyperhydration with glycerol has taken place, then consume 0.125 g/kg BW of glycerol in a volume equal to 5 mL/kg BW
Drinking fluid at a rate greater than that required to replace sweat loss (leading to a net weight gain during exercise) should be avoided. Therefore, if an athlete is hyperhydrated before exercise lasting ≤75 min, very little fluid would be needed during exercise under most conditions, and the consumption of glycerol with any fluid is not recommended
If no pre-exercise hyperhydration has taken place, then a larger dose of glycerol with fluid during exercise is warranted. Therefore, we recommend athletes consume 0.4 g/kg BW glycerol with fluid during each of the first 4 h of exercise After 4 h, individuals should consume fluid alone where necessary
It is recommended that smaller persons exercising at a lower intensity in cooler environments need to replace around 0.4 L/h, and this goes up to 0.8 L/h for heavier individuals exercising at higher intensities in warmer environments
Continual administration of glycerol over prolonged periods (e.g. >4 h) may lead to an accumulation of glycerol in the circulation. As such, continuing glycerol ingestion after 4 h is not advised

Each of these studies found that beverages containing glycerol were associated with significantly more rapid and complete restoration of plasma volume than water alone. In the Magal et al. study,[37] subjects became dehydrated by –2% and –3% BW for the glycerol and placebo trials, respectively, with corresponding plasma volume changes of –11% and –13%. Following rehydration, plasma volume remained at –4% compared with euhydrated baseline for the water alone trial, but increased to +2% for the glycerol trial. This restoration and expansion of plasma volume to greater than baseline levels in the glycerol trial occurred even though the subjects were still in a state of whole body dehydration (at the end of rehydration, subjects were still –1.5% BW for the glycerol trial and –2.5% BW for the water trial).[37] As such, plasma volume is restored before the interstitial and intracellular fluid compartments.[37]

The effect of glycerol on total body water is less defined. In the Magal et al.[37] study, urine volume was higher (by ~50 mL) and percentage fluid retention was lower (~5%) with glycerol compared with water. In the Kavouras et al.[21] study, urine volume was 385 mL lower with glycerol ($p > 0.05$), and in the Scheet et al.[46] study there was no difference in urine volume between the conditions. However, the influence of glycerol on total fluid retention might be related to rehydration duration. Kavouras et al.[21] and Magal et al.[37] monitored passive rehydration over 80 and 90 minutes, respectively. The data of Scheet et al.[46] indicate that benefits might be more pronounced with longer rehydration periods. In the glycerol trial, approximately 100 mL of urine was produced during each of the 3 hours. In the water trial, <100 mL total was produced in the first 2 hours, then urine output increased dramatically and ~300 mL was produced in the third hour. If this pattern continued, fluid excretion in the water trials would rapidly increase compared with the glycerol trial.

Replacing both the fluid and electrolyte deficits should be the goal after exercise.[18] Shirreffs et al.[76] showed that adequate sodium content is important to promote rehydration and to replenish sodium within the body, reducing the risk of hyponatraemia. If time permits, then post-exercise meals or salty snacks should be included with fluid to replace electrolyte deficits.[18,80] In this case, water should suffice as the rehydration fluid. If meals or snacks cannot be included, then carbohydrate-electrolyte solutions with relatively high sodium content might be more beneficial than drinking water alone at preventing the dilution of sodium, particularly in extracellular fluid.[18]

Table VI. Guidelines for fluid and glycerol consumption in rehydration

Consume 1.5 L of fluid for each 1 kg of weight loss
Add glycerol 1.0 g/kg bodyweight to each 1.5 L of fluid consumed, when a subsequent bout of exercise will be undertaken within a few hours (this will provide similar glycerol doses with fluid volumes as those used in hyperhydration)
If there is a long duration between successive exercise bouts, then rehydrate with water and meals and follow the pre-exercise hyperhydration recommendations before the next exercise session

Specific guidelines are difficult because the volume of fluid to be consumed will depend on the fluid deficit from sweat loss. Broad guidelines for fluid and glycerol consumption during rehydration are presented in table VI.

4. Areas for Further Investigation

We are recommending that individuals use glycerol with their beverage of choice. This is mainly due to the lack of studies that have compared the use of glycerol with different beverages (e.g. sports drinks vs water). Given that most athletes will use sports drinks due to the provision of additional carbohydrate and electrolytes, it is important to know whether consuming glycerol with a carbohydrate-electrolyte beverage would be more beneficial than glycerol with water. A randomized, controlled trial comparing glycerol in water with glycerol in a sports drink should be conducted.

5. Side Effects from Glycerol Consumption

The incidence of side effects associated with glycerol consumption in hyperhydration and rehydration is very low. Table I discusses the 26 studies that apply to the ingestion of glycerol with fluid consumed before, during or after exercise in warm/hot conditions. A further two investigations have looked at glycerol hyperhydration before exposure to cold environments.[81,82] Three of these 28 studies reported side effects after rapidly administering the glycerol as a concentrated bolus followed by fluid ingestion.[31,32,35] In two of these, a total of four subjects were nauseous after glycerol ingestion, resulting in the cancellation of the trial on that day,[31,32] while in the other, two subjects developed diarrhoea in the 24 hours after the trial.[35] A further three studies reported a low incidence of gastrointestinal distress (bloatedness) or light-headedness that did not affect participation.[36,40,44]

Side effects are more frequent when glycerol is consumed rapidly. This was considered when formulating the guidelines to consume solutions over 60 minutes. Many authors have used the doses of glycerol and fluid that we have recommended, over the proposed time frames, without incidence. However, should an athlete be unable to tolerate these protocols, it is recommended that they lower the concentration of glycerol, and/or consume the solution over a period of 90 minutes instead of 60 minutes.

Of the two studies using glycerol during exercise without pre-exercise hyperhydration, side effects were seen in one,[44] but not the other.[45] Murray et al.[44] gave a higher dose, with less fluid, which when combined with delayed gastric emptying with exercise may account for the symptoms present. Three other studies hyperhydrated with glycerol pre-exercise and then provided small doses of glycerol with fluid while exercising, and also reported no side effects.[20,30,42] Again, these factors were considered when formulating the guidelines. If the recommended doses cause gastrointestinal upset, then the concentration of glycerol should be lowered.

While glycerol has also been used clinically to reduce cerebral oedema, intracranial hypertension and intraocular pressure by drawing water out of the CSF and brain,[83-85] there is very little chance of these events occurring when glycerol is consumed with large volumes of fluid. However, the risk would increase if glycerol accumulates following multiple large glycerol doses over extended periods, especially when dehydrated. Thus, the recommendations are for glycerol use for periods of up to 4 hours. Finally, there are certain populations for which glycerol ingestion is not advised due to actions on liver gluconeogenesis, kidney filtration, cardiovascular homeostasis and hydration homeostasis. These include pregnant females and individuals with diabetes, renal disease, migraine and headache disorders, cardiovascular disease and liver disorders.[23,83]

6. Summary and Recommendations

This paper provides guidelines for the use of glycerol before, during and after exercise. Pre-exercise glycerol hyperhydration is likely to benefit the athlete during exercise in which a 2% BW reduction will occur, by attenuating dehydration. Furthermore, glycerol consumption with fluid during exercise and in rehydration is likely to maintain cardiovascular function and enhance the restoration of body water deficits. However, as with any proposed ergogenic aid, athletes are advised to trial using glycerol during training before deciding to use it during competition.

If athletes fall into any of the 'at-risk' populations, it is recommended that glycerol is avoided or used only in consultation with their physician. Furthermore, all athletes are advised to discontinue using glycerol if they continually experience any associated side effects. If side effects do present, athletes are advised to trial different glycerol concentrations and fluid volumes to ascertain whether they may be able to develop an individualized protocol to still gain some benefit.

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