Title

Optimizing the restoration and maintenance of fluid balance after exercise-induced dehydration

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Running Head

Optimizing post-exercise rehydration

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Abstract

Hypohydration, or a body water deficit, is a common occurrence in athletes and recreational exercisers following the completion of an exercise session. For those who will undertake a further exercise session that day, it is important to replace water losses to avoid beginning the next exercise session hypohydrated and the potential detrimental effects on performance that this may lead to. The aim of this review is to provide an overview of the research related to factors that may affect post-exercise rehydration. Research in this area has focused on the volume of fluid to be ingested, the rate of fluid ingestion and on fluid composition. Volume replacement during recovery should exceed that lost during exercise to allow for ongoing water loss however ingestion of large volumes of plain water results in a prompt diuresis, effectively preventing longer term maintenance of water balance. Addition of sodium to a rehydration solution is beneficial for maintenance of fluid balance due to its effect on extracellular fluid osmolality and volume. The addition of macronutrients, such as carbohydrate and protein, can promote maintenance of hydration by influencing absorption and distribution of ingested water which, in turn, effects extracellular fluid osmolality and volume. Alcohol is commonly consumed in the post-exercise period and may influence post-exercise rehydration as will the co-ingestion of food. Future research in this area should focus on providing information related to optimal rates of fluid ingestion, advisable solutions to ingest during different duration recovery periods and confirmation of mechanistic explanations for the observations outlined.

Key Words

Rehydration; Sodium; Carbohydrate; Protein; Alcohol

Introduction

Human body water accounts for 50-70% of body mass, depending on body composition, but despite this abundance, body water is regulated within narrow ranges. Euhydration is defined as a body mass within ± 0.2% of normal in temperate environments and ± 0.5% of normal in hot environments or during exercise (18), with hyper or hypohydration occurring above or below these limits. Both large reductions and large increases in body water can lead to adverse health consequences. If combined with high ambient temperature and humidity, hypohydration can result in heat syncope due to venous pooling and reduced blood flow to the brain (3) and heat exhaustion due to hypotension and central fatigue (27). Exertional heat stroke may occur due to high levels of metabolic heat production, an inability to dissipate heat or a combination of both factors. This leads to large increases in core body temperature and initial symptoms such as central nervous system dysfunction which, if allowed to progress, can lead to systemic inflammation that can be fatal (29). Over-hydration may occur due to excessive ingestion of hypotonic fluids, an electrolyte deficit and/or a failure of the renal system to compensate for these disturbances (19). If extracellular fluid sodium concentration significantly reduces, water is moved from the interstitial to the intracellular space resulting in cell swelling which may lead to central nervous system dysfunction (28). A number of case studies have demonstrated the effects of changes in body water, in combination with environmental stress, on physiological function (19, 43).

During exercise, increased metabolic heat production causes an increase in core temperature and initiation of evaporative cooling in an attempt to limit the rise in core temperature. If fluid ingestion is less than fluid loss, hypohydration develops and is commonly present at the end of exercise bouts. In such situations, post-exercise fluid ingestion is necessary to restore fluid balance. Whilst current guidelines (49, 59) recommend structured rehydration only if the time between exercise sessions is short (i.e. <24 hours) or the extent of hypohydration is large (i.e. >5% body mass), the prevalence of urine hyperosmolality at the start of exercise sessions in athletes training on a daily basis (34, 37, 38, 63) suggests that many athletes potentially begin exercise in a hypohydrated state.

It is generally accepted that commencing exercise in a hypohydrated state will impair exercise performance, particularly if the exercise task is prolonged and/or is undertaken in a hot environment (5, 49, 50). Whilst the majority of this literature suggests body water deficits equivalent to ~2% body mass might impair performance, more recent evidence derived from studies where participants have been blinded to their hydration status (4) or have been repeatedly exposed to the dehydration stimulus (16) suggest the effects might be less deleterious. Nonetheless, commencing exercise in a euhydrated state is likely to offer the best strategy to optimize exercise performance in most settings. Where water losses are small and recovery time prolonged, an aggressive rehydration strategy is not necessary as fluid balance should be restored as a result of normal water and food intake. When recovery time is short, more attention is needed to restore and maintain fluid balance after exercise, as thirst-driven fluid intake is often inadequate to restore water balance in the short term (58), even when fluid is ingested with a meal (6). This mini-review is focused on rehydration strategies for such situations in humans.

Post-exercise rehydration has been the subject of several previous reviews (53, 55), but a full review on this topic has not been undertaken for some time despite a significant volume of new work emerging. The aim of this review is therefore to summarize the current research and advise on the restoration and maintenance of fluid balance after exercise-induced dehydration.

Most of the studies included in this mini-review have followed a format similar to that outlined by Maughan et al (35), with only minor variations. Experimental protocols tend to involve intermittent exercise, usually in the heat, to induce a body water deficit of ~2% of the pre-exercise body mass. Test drinks are ingested, usually over a period of 30-60 minutes, either in a pre-determined volume or ad libitum. Urine (and sometimes blood) samples are collected before and after exercise and at intervals for up to 6 hours after fluid ingestion. The assumptions in this experimental model include that mass loss during exercise equates to water (sweat) loss only and does not include other potential mechanisms of water output and that the volume of fluid passed during the recovery period reflects the changing hydration status. There are some errors in the assumption that body mass change during exercise represents sweat loss (36), but these are relatively small and as exercise is undertaken in all trials, are consistent between trials. Post-exercise, participants rest in a temperate environment without access to foods. Thus the assumption that urine excretion represents water loss is valid as other avenues of water loss are likely to be very small and consistent between trials.

Drink volume

Since fluid must be ingested to restore body water when hypohydrated, the volume of drink consumed is critical for ensuring a return to euhydration. Exercise in the heat leads to a marked reduction in plasma volume and increase in plasma osmolality which is, at least in part, due to hypohydration resulting from sweat loss (44). Increased plasma osmolality is the main physiological driver for arginine vasopressin (AVP) secretion from the posterior pituitary (48), leading to increased water reabsorption in the nephron and reduced urine output. However, even in a hypohydrated state, obligatory water losses continue to allow the excretion of metabolic waste products persist. Consequently, a volume of fluid greater than that lost during exercise is required to restore water balance. Shirreffs et al. (60) provided a fluid volume of 50, 100, 150 or 200% of body mass loss in the hour after exercise, reporting participants did not return to a state of euhydration unless a volume of fluid greater than that lost during exercise was consumed. These volumes were tested with sodium concentrations of 23 mmol/l and 61 mmol/l, with only the higher concentration sodium fluid demonstrating enhanced rehydration with a drink volume of 200% vs 150%. This suggests that ingesting 1.5 litres of a low sodium drink for every 1 litre of fluid loss during exercise achieves rehydration without resulting in large reductions in plasma sodium levels. Similarly, Mitchell et al. (41) observed that ingesting a hypotonic electrolyte drink in a volume amounting to 150% of body mass loss during exercise resulted in enhanced rehydration three hours later compared to when 100% of body mass loss was ingested.

Rate of drink ingestion

Rapid ingestion of a large volume of hypotonic fluid may increase blood volume and consequently reduce plasma osmolality and AVP release (48), resulting in increased urine production. Despite this being an important consideration, there are very few studies that have specifically examined whether the rate at which fluid is ingested impacts the effectiveness of a rehydration protocol. Archer and Shirreffs (1) observed that cumulative urine volume was greater when a volume of isotonic sports drink equivalent to 150% body mass loss was ingested over 30 minutes compared to 90 minutes. Similarly, Jones et al. (26) observed that post-exercise rehydration was greater at the end of an 8 hour recovery period when water in a volume equivalent to 100% fluid losses was consumed over 4 hours compared to over 1 hour. Whilst urine losses over the 8 hour recovery period in this study (26) were relatively low in both trials (420 mL and 700 mL), the inadequate water intake provided meant participants were never fully rehydrated during the protocol.

It seems clear from what little data is available that ingesting a given volume over a longer period of time is likely to result in more efficient rehydration given the likely effects that this will have on fluid balance mechanisms. The optimal rate of fluid ingestion to maximize rehydration efficiency between exercise bouts is currently unclear and should be an area of future research.

Drink composition

Ingestion of plain water is not effective at maintaining fluid balance during recovery, as this results in large reductions in plasma sodium concentration and osmolality (44) which lead to diuresis. Consequently, the formulation of rehydration drinks should aim to avoid large reductions in plasma osmolality following ingestion. This can be achieved either by the addition of certain solutes, such as sodium, that directly affect plasma osmolality or by reducing the overall rate of fluid absorption, avoiding acute changes in plasma osmolality and AVP secretion.

Sodium

Sodium is the main cation in the extracellular fluid and, therefore, has a large effect on plasma osmolality. It is also the most abundant electrolyte in sweat, with a typical range of 20-80 mmol/L (2). Consequently, much research has focused on the sodium content of post-exercise rehydration drinks. Shirreffs et al. (60) observed an interaction between drink volume, drink sodium content and whole body rehydration. Effective rehydration was achieved only when the volume of fluid ingested was greater than the volume of fluid lost and when the drink sodium concentration was higher than that of sweat. A number of studies have now systematically investigated the effect of sodium concentration of rehydration drinks on the restoration of fluid balance (32, 39, 57), clearly demonstrating that urine output decreases as drink sodium concentration increases. It appears that the addition of sodium at a concentration equal to or greater than that of the sweat lost is required to maintain positive fluid balance. These concentrations are somewhat higher than those typically found in commercial carbohydrate-electrolyte sports drinks (about 20-25 mmol/L). It is possible, however, that the ingestion of the large amounts of sodium necessary to achieve this may result in increased urinary potassium loss, with unknown consequences (57).

Potassium

Potassium is the main cation in the intracellular fluid and is lost in relatively small amounts in sweat (typically 4 – 8 mmol/L) (31). Potassium loss is, therefore, relatively low even at high sweat rates and unlikely to cause significant health consequences such as hypokalemia. Yawata (68) thermally dehydrated rats to an extent that weight was reduced by 9% before *ad libitum* rehydration over a 17 hour period with either tap water, an NaCl or KCl drink. Recovery of intracellular fluid volume tended to be greater when KCl was provided compared to NaCl, although beneficial effects were modest, suggesting that the addition of potassium to a rehydration drink may aid in overall water retention by regulating the level of intracellular fluid. Maughan et al (35), reported enhanced post-exercise rehydration after ingestion of a 25 mmol/L KCl drink compared to a 90 mmol/L glucose drink, with a 60 mmol/L NaCl drink and a drink containing all three ingredients responding similarly to the 25 mmol/L KCl drink. In contrast, Shirreffs et al. (54) observed no difference in post-exercise rehydration between a 30 mmol/L potassium, 8 mmol/L sodium drink and two brands of mineral water ingested in a volume equal to 150% of body mass loss. However, four hours after rehydration, participants were considered euhydrated following ingestion of a sports drink and hypohydrated on all other trials, suggesting that increasing potassium concentration did not enhance fluid balance after exercise. More recently, Perez-Idarraga and Aragon-Vargas (46) reported similarly enhanced rehydration with a sports drink and a potassium containing drink (fresh coconut water) and another potassium-rich drink compared to bottled water.

The interpretation of the studies reviewed is complicated by the presence of chloride in drinks in some studies, but not others. As the major anion in the extracellular space, the inclusion of chloride in drinks containing potassium, might help to explain why some studies have reported enhanced rehydration of potassium-containing drinks (35, 46) and others have not (54).

Carbohydrate

Evans et al. (12) investigated the effects of ingesting 600 mL of a 0, 2, 5 or 10% glucose drinks on calculated changes in plasma volume over the subsequent hour. A hyperosmotic 10% glucose drink resulted in significant reductions in plasma volume amounting to 2.2% (or approximately 100 mL) over the following hour. This was likely caused by the movement of water into the intestinal lumen in response to the concentration gradient that is established following ingestion. This may be beneficial for post-exercise rehydration as it may reduce the rate of overall fluid uptake, which may influence fluid balance mechanisms and, ultimately, maintenance of fluid balance after rehydration. Evans et al. (13) demonstrated a greater percentage of fluid was retained at the end of a six hour recovery period when a drink containing 10% glucose was ingested compared to a drink containing 0% glucose. Drink volume amounted to 150% of fluid loss during exercise. Similarly, Osterberg et al. (45) reported that fluid retention was greatest four hours after exercise when higher amounts of carbohydrate (6% and 10%) were present in rehydration drinks ingested in a volume equal to 100% of body mass loss during exercise. These studies suggest that the addition of carbohydrate, and particularly glucose, to a rehydration drink enhances post-exercise rehydration. A potential side effect of this is a feeling of bloating and fullness when drinks are ingested in volumes equivalent to 150% body mass lost during exercise (13), raising the question of whether individuals would ingest the required volume in situations of voluntary fluid intake. Evans et al. (14) demonstrated that 10% glucose drink was as effective as 0% and 2% glucose drinks at restoring and maintaining fluid balance post-exercise when participants were given *ad libitum* access to fluids over a two hour rehydration period. This suggests individuals ingest sufficient high carbohydrate drink in voluntary drinking situations to restore body water levels however this does not necessarily result in fluid balance benefit compared to a hypotonic drink. Whereas the mechanism for the effectiveness of sodium in a rehydration drink is due to its effect on plasma sodium concentrations, osmolality and AVP release, Clayton et al. (6) reported that the reduced urine output, and resultant maintenance of euhydration during recovery, following ingestion of high carbohydrate drinks post-exercise appears to be due to a reduction in gastric emptying rate and, therefore, overall fluid absorption. Collectively, these studies suggest that the addition of carbohydrate to rehydration drinks enhances fluid retention if the concentration of carbohydrate, and volume of fluid ingested, is sufficiently high.

Protein

A number of studies have examined the effect of protein-containing drinks on post-exercise rehydration. Milk and milk-based drinks have been shown to enhance post-exercise rehydration compared to carbohydrate-electrolyte drinks and/ or water (9, 22, 51, 61, 66). Milk is a complex drink; containing sodium, potassium, carbohydrate and protein, constituents which may all independently positively influence rehydration either by effecting the composition of the extracellular fluid or by reducing the overall rate of fluid absorption. Whilst milk contains sodium and carbohydrate in concentrations similar to carbohydrate-electrolyte sports drinks (51), milk also contains protein, which is not typically found in commercially available rehydration drinks. Subsequently, the effect of protein addition to post-exercise rehydration drinks has been examined. The addition of protein to a rehydration drink may be of benefit as, in addition to potentially affecting fluid balance, protein ingestion after exercise has been demonstrated to increase muscle protein synthesis (67). James et al. (23, 24) reported enhanced rehydration with combined carbohydrate and milk protein drinks compared to energy-matched carbohydrate-only drinks. Similarly, Seifert et al. (52) reported enhanced rehydration with the addition of 1.5% whey protein to a 6%

carbohydrate-electrolyte drink, with drinks ingested in a volume equivalent to the body mass loss during exercise. Subsequent investigations have reported no benefit of adding whey protein to rehydration drinks either when energy is matched (24) or not (20, 25), when the drink is consumed in a volume equal to 150% of the body mass loss during exercise. What accounts for these contrasting findings is not clear, but it might be related to the lower relative fluid intake volume in the study of Seifert et al. (52). Additionally, some studies of specific amino acids, suggest increased intestinal sodium and/ or water uptake (64, 65, 69), which might consequently enhance rehydration. Potential mechanisms by which protein-containing drinks might enhance post-exercise rehydration seem most likely to be related to a slowing of the overall rate of fluid uptake and/ or an increase in plasma albumin content and thus oncotic pressure. Clearly, additional work is needed to fully elucidate these mechanisms and possibly better understand the impact of specific amino acids, but any effect of protein on post-exercise rehydration is likely to be small. However, in situations where protein might be recommended to enhance other aspects of recovery, its addition to a recovery drink is unlikely to impair rehydration and may, depending on the type of protein present, enhance rehydration.

Figure one outlines the main variables associated with restoration and maintenance of whole body fluid balance after exercise and their likely mechanism of action.

Alcohol

Alcohol has a well-recognised diuretic effect (11). This is largely thought to be due to a direct effect of alcohol on the release of AVP from the posterior pituitary (42) although there may also be some direct effects of alcohol on renal absorption (30, 62). This suggests that ingestion of alcohol-containing drinks after exercise should be avoided if rehydration is the primary goal. Recently, however, Hobson and Maughan (21) have demonstrated that the diuretic effects of beer are blunted when individuals are hypohydrated. In this study, participants were dehydrated by exercise in the evening on four occasions. On two occasions participants were fed and rehydrated before returning to the laboratory in the morning and ingesting one litre of beer (4% alcohol) or non-alcoholic beer. On the other two occasions, participants were fed after exercise but were not rehydrated and returned the next morning and repeated the experimental protocol. Urine volume over the following four hours was increased after the ingestion of an alcoholic drink when euhydrated, but not hypohydrated. It is likely that the blunting of the diuretic response to alcohol ingestion when hypohydrated is due to renal water conservation. In this study, urine output was still greater when alcohol was ingested while hypohydrated (though not significantly) suggesting that there might still be some effect of alcohol on renal function with hypohydration. This observation may, therefore, have consequences for the addition of alcohol to a post-exercise rehydration drink.

Shirreffs and Maughan (56) investigated the effectiveness of rehydration drinks containing 0, 1, 2 or 4% alcohol, provided in a volume equal to 150% body mass loss during exercise. Peak blood ethanol concentration on each trial was measured at 0, 2, 7 and 21 mmol/L during the 0, 1, 2 and 4% alcohol trials respectively. Urine output over the six hour recovery period tended to be increased as the alcohol content of the drink increased (median cumulative urine output was 942, 1108, 1184 and 1457 mL on the 0, 1, 2 and 4% trials, respectively) and recovery was not impaired when the drink contained up to 2% alcohol. Similarly, Flores-Salamanca and Aragon-Vargas (17) observed that urine output was greater when participants rehydrated with 4% beer (peak blood ethanol concentration of 0.857 g/L (~19 mmol/L)) compared to low alcohol beer and water (no increase in blood ethanol concentration) although in this study a volume equivalent of 100% body mass lost was ingested. Desbrow et al. (10) compared the effectiveness of low alcohol beer (2.3% alcohol), low alcohol beer with 25 mmol/L added sodium, beer (4.8% alcohol) or beer with 25 mmol/L added sodium following exercise-induced dehydration. Drink volume was equivalent to 150% body mass loss during exercise over a one hour period. Over the subsequent four hour recovery period, urine volume was lowest in the low alcohol beer with added sodium trial. More recently, Desbrow et al (8) further manipulated the alcohol and sodium content of beer ingested after exercise-induced dehydration. They found that the electrolyte concentration of low-alcohol beer seemed to have a greater effect on post-exercise fluid retention than small changes in alcohol content.

The available evidence outlined suggests that the addition of small amounts of alcohol to rehydration drinks is unlikely to inhibit the rehydration process although this is unlikely to be recommended between bouts of exercise on the same day.

Food and fluid ingestion

The studies cited above have established the importance of replacement of electrolyte losses as well as the addition of macronutrients to fluids intended to promote post-exercise rehydration. However, no food was ingested during the post-exercise recovery period in the majority of these studies, and most athletes would not avoid food for such a prolonged period after exercise. The ingestion of food will add water, solutes and macronutrients to those present in any drinks consumed and may overwhelm any effects caused by drink composition. Despite this, few studies have investigated the effects of the co-ingestion of food and fluid on post-exercise rehydration.

After exercise-induced dehydration, Maughan et al. (33) rehydrated participants with ingestion of either a commercially-available sports drink or a solid meal with flavored water. This study was designed so that water ingestion (from food and fluids) was exactly 150% of body mass loss during exercise in both trials. Fluid retention after the six hour recovery period was greater when plain water was ingested with a solid meal, and this difference was attributed to the greater electrolyte intake in this trial. Ray et al. (47) dehydrated participants by 2.5% body mass before a two hour rehydration period, which consisted of ingestion of water, a carbohydrate-electrolyte drink, chicken broth or chicken noodle soup. Water intake during this period amounted to 100% body mass loss during exercise. Fluid retention was highest in the liquid meal trials, but again this study did not match electrolyte content.

Recently, Miller et al. (40) compared the effectiveness of water and a 50 mmol/L sodium chloride drink following exercise-induced dehydration when a standard meal was consumed during both trials. Test drink volume amounted to 150% of body mass loss during exercise. Fluid retention was greater when the sodium chloride drink was ingested. Using a similar protocol, Evans et al. (15) reported that there was no difference in fluid retention between water and a sports drink when a standard meal was ingested during the rehydration period.

Although more work is needed in this area, these results suggest that water is likely to be an effective rehydration drink when ingested alongside solid food, provided a sufficient volume of fluid is ingested.

Conclusion

Given the effect of hypohydration on physiological function and exercise performance, an appropriate post-exercise rehydration strategy is necessary to promote effective recovery and avoid detrimental effects on subsequent exercise sessions. For complete recovery of fluid balance to occur, a volume of fluid greater than that lost during exercise must be ingested to allow for ongoing urine losses. Where possible, ingestion of large volumes in a short period of time should be avoided and intake should be spread over several hours.

To achieve effective restoration of body water and to retain ingested water, electrolytes lost in sweat must also be replaced. The addition of sodium at a concentration greater than that of sweat appears to be necessary, but a lower concentration may be effective if ingested in a larger volume. The addition of potassium to a rehydration drink does not appear to exert a major influence on maintenance of fluid balance after exercise. The addition of carbohydrate and milk protein appears to be beneficial to the rehydration process due to a reduced rate of fluid uptake. In addition, this provides a means for glycogen and protein synthesis.

Milk appears to be an effective rehydration drink because of its sodium, carbohydrate and protein content. The addition of small amounts of alcohol to a rehydration drink does not appear to adversely affect the rehydration process, but drinks with more than 2% alcohol are likely to impair rehydration.

While plain water is not considered to be an effective rehydration drink when consumed on its own, it is likely to be effective if consumed with a meal which contains adequate electrolytes. This is an area that requires further investigation.

Future research related to the area of post-exercise rehydration should aim to further elucidate mechanisms for some of the observations described in this manuscript, as well as focus on optimizing rehydration strategies for different exercise contexts. This research should focus on what the optimal rate of fluid ingestion may be and the effectiveness of rehydration strategies when recovery time between exercise sessions is of differing lengths. In addition, this mini-review has focused on dehydration induced via acute exercise in the heat and subsequent drink ingestion. Further research is required on other mechanisms, such as dehydration resulting from passive heat exposure or chronic fluid restriction, given that these may result in differing effects on intra- and extracellular fluid composition therefore potentially influencing the rehydration process.

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Figure Legends

Figure 1: Schematic diagram outlining the major factors involved in restoring and maintaining fluid balance in the post-exercise period. ECF = Extracellular Fluid.