

Effects of Metered Versus Bolus Water Consumption on Urine Production and Rehydration

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This study compared the effects of a rapid bolus and a slower metered water-consumption rate on urine production and postexercise rehydration. Participants ($n = 8$) dehydrated by 2% body weight through moderate exercise in an environmentally controlled chamber (35 °C, 55% relative humidity). Breakfast and lunch were standardized for all participants during each 8-hr data-collection period. Rehydration was performed using a volume of water equal to that lost during exercise either as bolus consumption (100% of volume consumed in 1 hr; BOL) or metered consumption (12.5% of volume every 30 min for 4 hr; MET). Urine volume was used to assess hydration efficiency (water retained vs. water lost) and net fluid balance at 8 hr. Mean urine outputs were 420 ml (MET) and 700 ml (BOL). A paired-samples t test showed that hydration efficiency was greater for MET (75%) than for BOL (55%; $p = .018$). These data suggest that metered administration was more effective in maintaining fluid balance. These findings suggest that rehydration rate is a factor in fluid-balance response. For situations in which available fluid volume is restricted, greater hydration efficiency is highly desirable.

Keywords: hydration, fluid balance, fluid administration

Hypohydration before, during, and after exercise and work can greatly hinder performance, as well as threaten the health of an athlete or worker (Maughan, Leiper, & Shirreffs, 1997). Heat illness and death among athletes and frequent heat injuries among workers during summer months emphasize the need for proper hydration among individuals prone to high levels of hypohydration ($\geq 2\%$).

Much of the research performed to date has focused on optimal methods of rehydration (i.e., beverage composition and volume consumed) after exercise-induced hypohydration. Successful rehydration is a function of the volume of fluid consumed versus total fluid losses. To compensate for fluid loss from urine production during rehydration, studies by Maughan, Leiper, and Shirreffs (1996) and Shirreffs and Maughan (1998) have shown that to adequately reach and maintain a euhydrated state for a period of 2–5 hr, a volume of 150% of the fluid lost should be consumed (Maughan et al., 1997; Shirreffs & Maughan, 1998).

Rapid rehydration techniques ranging from 30 min to 3 hr have been commonly used in assessing optimal volume consumption, beverage composition, and total rehydration (Maughan et al., 1996; Mitchell, Grandjean, Pizza, Starling, & Holtz, 1994; Shirreffs & Maughan,

1998; Stachenfeld, Gleim, Zabetakis, & Nicholas, 1996). Table 1 can be interpreted at least two ways. One is that the kidneys' response to a rapid rate of ingested fluid was to overcompensate and produce more urine than when the rate of consumption was slow. Alternatively, Table 1 may also suggest that differences among studies in the volume of urine output may result from differences in total volume of fluid consumption alone, thereby indicating the need for a direct comparison of consumption rates at the same specified volume.

A large amount of urine production during rapid rehydration may be the result of the body's endocrine system overcompensating during rehydration after dehydration (Mitchell et al., 1994). Mitchell et al. postulated that the duration of the rehydration trial and obligatory urine production may be related, in that a slower rate of administration may prevent the formation of large volumes of urine associated with rapid fluid-consumption rates (see Table 1). Using a high and low rate of carbohydrate-electrolyte consumption after dehydration, Kovacs, Schmahl, Senden, and Brouns (2002) found that total urine outputs were not significantly different between high- and low-rate groups. However, the high rate of ingestion in their study consisted of consuming fluids over a period of 3 hr postdehydration versus 5 hr in low rate of ingestion. The apparent "metering" of both fluid-ingestion groups may have led to the similar results reported between the two treatments.

What has yet to be investigated is the time course of fluid administration between two largely different ingestion rates using water as the rehydrating fluid. We

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Table 1 Comparison of Urine Output During Various Administration Techniques and Volumes of Consumption During 4 hr of Collection Postdehydration

Authors	Rehydration time period	Urine output (ml)	Volume consumed (ml)	% hydration efficiency	% body weight loss/% volume consumed
Costill & Sparks, 1973	Every 15 min for 3 hr	610	2,743	78	4/100
Maughan & Leiper, 1995	1 hr	1,250	2,000	38	2/150
Shirreffs & Maughan, 1998	1 hr	1,082	1,938	43	2/150
Gonzalez-Alonso, Heaps, & Coyle, 1992 ^a	1 hr	600	1,958	70	2.5/100

Note. Urine output refers to amount of urine produced. % hydration efficiency = volume retained/volume consumed.

^aUrine collection time of 2 hr.

hypothesized that if the kidneys are presented with a lesser challenge, that is, if the rate of fluid ingested is sufficiently slower, overcompensation by the kidneys can be prevented, and hydration efficiency (fluid retained/fluid consumed) improved.

If an optimal volume for maintaining positive fluid balance could be coupled with a more effective administration of fluids during rehydration, urine loss might be decreased and, consequently, total rehydration improved. Of particular interest may be military missions, wildland firefighting, and survival situations, where the volume of potable water may be limited and the ability to maximize the utility of those limited fluids may be crucial. Therefore, the purpose of the current study was to compare the effects of bolus versus metered water consumption on urine production and total rehydration. We hypothesized that metered fluid consumption would result in less fluid lost to urine, increasing the effectiveness of a given volume of rehydration beverage.

Methods

Eight healthy men volunteered to participate in this study. Power analysis using means and standard deviations from Lambert et al. (1992) revealed that a difference of 138 ml of urine output between means could be detected with .80 power at an alpha level of .05 using 8 participants. Previous research has shown mean urine volume differences far exceeding 138 ml (see Table 1).

In accordance with the local institutional review board, all research was approved, and written consent was obtained from all participants before testing. Descriptive statistics for participants are presented in Table 2. Participants were instructed about procedures of the research before testing. For standardization across trials, they were asked to document food and fluid consumption for the day before testing and to fast for 12 hr the night before testing, with the exception of ingesting approximately 500 ml of water at 9 p.m. to help ensure euhydration the following day (Lambert et al., 1992; Maughan et al., 1996). Participants were also asked to abstain from any fluid or food consumption outside of what was provided on the

Table 2 Descriptive Characteristics of Participants

	<i>M</i>	<i>SD</i>
Age (years)	32.3	9.5
Height (cm)	178.5	4.0
Mass (kg)	78.0	11.2
Body fat (%)	11.2	3.1
Weight loss (kg)	1.59	0.21
Body weight (% loss)	2.04	0.14
Dehydration time (min) ^a	75.6	14.2
Sweat rate (ml/hr)	1,317	359
Run speed (m/min)	147.4	24.12
Walk speed (m/min)	91.1	7.77

^aMean amount of time needed to dehydrate participants.

day of testing and to abstain from strenuous exercise on the day before and the day of testing.

On entering the laboratory, to determine predehydration weight, participants emptied their bladders and then were weighed (Detecto Scale, Brooklyn, NY). Dehydration was induced by moderate physical activity (self-selected intensities) consisting of periods of running followed by periods of walking (Quinton Treadmill, Seattle WA) duplicated within participants for both trials in a climate-controlled chamber at a mean temperature of 35 °C and a mean relative humidity of 55% (Isothermex, Columbus Instruments, Columbus OH.). Core temperature was monitored using a rectal probe (Physitemp, Clifton, NJ). A rectal temperature of ≤ 38.7 °C was set as the criterion for removal of participants from the climate-controlled environment. After the initial 40 min of exercise, every 15 min participants undressed, dried off, and weighed until a 2% decrease in body mass was achieved. Postdehydration weight subtracted from predehydration was used to estimate the amount of body fluid lost. After dehydration of 2% of body mass, to maximize external validity and mimic normal behaviors of athletes and workers, participants were fed a light

breakfast (breakfast and lunch composition and times of consumption were standardized among participants) and were given water and instructions about its consumption. For rehydration purposes, water without electrolytes has been shown to be less effective because of prompt diuresis even in hypohydrated states (Costill & Sparks, 1973; Maughan & Leiper, 1995). However, the lack of accessibility to an electrolyte beverage in many populations and situations requires that rehydration must often be accomplished with water alone.

Standardized meals consisted of a breakfast bar (Kellogg's NutriGrain; Na⁺ = 120 mg, water = 1.76 ml) and a banana (Na⁺ = 1 mg, water = 88 ml) for breakfast. Lunch consisted of a peanut butter and jelly sandwich and a 28-g serving of potato chips (Frito Lay's; Na⁺ = 700 mg, water = 28 ml). Total water content was 116 ml. Total Na⁺ and water content for both standardized meals were obtained from the U.S. Department of Agriculture (www.nal.usda.gov/fnic/foodcomp/search). Participants were administered breakfast immediately after dehydration trials, and lunch was administered at the midway point (4 hr) of the 8-hr data-collection period.

Fluid-administration rates were counterbalanced among participants to minimize the impact of order effects. Participants were provided with a volume of water that was equal to 100% of the estimated fluid loss during exercise-induced dehydration. This volume was chosen because our hypothesis concerned the efficacy of slowing fluid presentation to the kidneys. If too much fluid is presented to the kidneys, even slowly, homeostasis demands obligatory fluid removal, thus dampening the treatment (Verney, 1946).

There were two techniques of rehydration fluid administration. In one, a large bolus equal to 100% of fluid lost was consumed within 60 min of the completion of exercise. In the other, termed metered rehydration, there was intermittent consumption during 4 hr after exercise of a volume equal to 100% of estimated fluid lost. Metered consumption was ingestion of 12.5% of the total volume consumed eight times (immediately and every 30 min for 4 hr). Both trials were completed on the same day of the week, with 7 days separating them, to avoid confounds of variable daily habits. For the same reason, no trials were conducted on Mondays.

Urine was collected for 8 hr after the dehydration protocol during both fluid-administration trials. Each urine sample was collected separately to assess the rate of production across time. Total urine production over the 8-hr collection period was used to assess hydration efficiency (ratio of volume of fluid retained to volume of fluid ingested). Urine-collection times could not be standardized among participants because urination was voluntary.

The variable of greatest importance was hydration efficiency, a ratio of the amount of fluid retained to the amount of fluid ingested. Repeated-measures ANOVA was used to determine significant differences in rate of urine production within and between trials. Paired-sample *t* tests were used to determine differences between

metered and bolus drinking for key variables. An alpha level of $p \leq .05$ was set to establish significance. Unless otherwise indicated, all data represent $N = 8$ and are presented as $M \pm SD$.

Results

Descriptive participant data are presented in Table 2. Weight loss during heat exposure is expressed as percent body-weight loss. Mean weight loss among participants was 1.60 ± 0.18 and 1.59 ± 0.21 kg for bolus and metered trials, respectively. All participants completed all trials. Net fluid balance (NFB) for both bolus and metered consumption are shown in Figure 1. Mean fluid intakes for all participants were $1,607 \pm 185$ and $1,590 \pm 210$ ml for bolus and metered trials, respectively. Mean urine production for the bolus trial was 700 ± 220 ml, significantly higher ($p = .018$) than in the metered-consumption trial, 420 ± 203 ml (Figure 2). Mean hydration efficiency as calculated by fluid retained/fluid consumed was $55\% \pm 18\%$ and $75\% \pm 12\%$ for bolus and metered techniques, respectively ($p = .028$). The mean rate of urine production between trials was examined for the first 4 hr and second 4 hr of collection. Urine production was 178 ± 184 ml in the first 4 hr for the metered trial, which was significantly lower ($p = .02$) than the first 4 hr of the bolus trial, 428 ± 216 ml. No significant differences were found ($p = .45$) between metered (242 ± 153 ml) and bolus (271 ± 98 ml) trials during the second 4 hr of collection.

Discussion

This study compared the efficacy of bolus versus metered water consumption on urine production and total rehydration. We hypothesized that metered fluid consumption would result in less fluid lost to urine, thereby increasing the effectiveness of a given volume of rehydration beverage. Results revealed a 20% increase in hydration efficiency ($p = .028$) with metered consumption (75% hydration efficiency) compared with bolus consumption (55% hydration efficiency).

These findings support data from a similar study that indirectly addressed this issue. In that study a similar 3-hr metered rehydration period (participants drank every 15 min) showed 78% hydration efficiency (Costill & Sparks, 1973). When comparing data from the current study and that of Costill and Sparks with the previous work of Maughan (2003), Maughan et al. (1997), Shirreffs and Maughan (2000), and Gonzalez-Alonso et al. (1992; see Table 1), it appears that large bolus ingestions of water consumed over short periods of time overstimulate the kidneys, leading to increased urine production and decreased hydration efficiency. This overstimulation is necessary to maintain homeostatic regulation of blood volume and blood osmolality (Gauer & Henry, 1963; Verney, 1946).

Whereas blood volume and osmolality were not measured in the current study, bolus water consumption

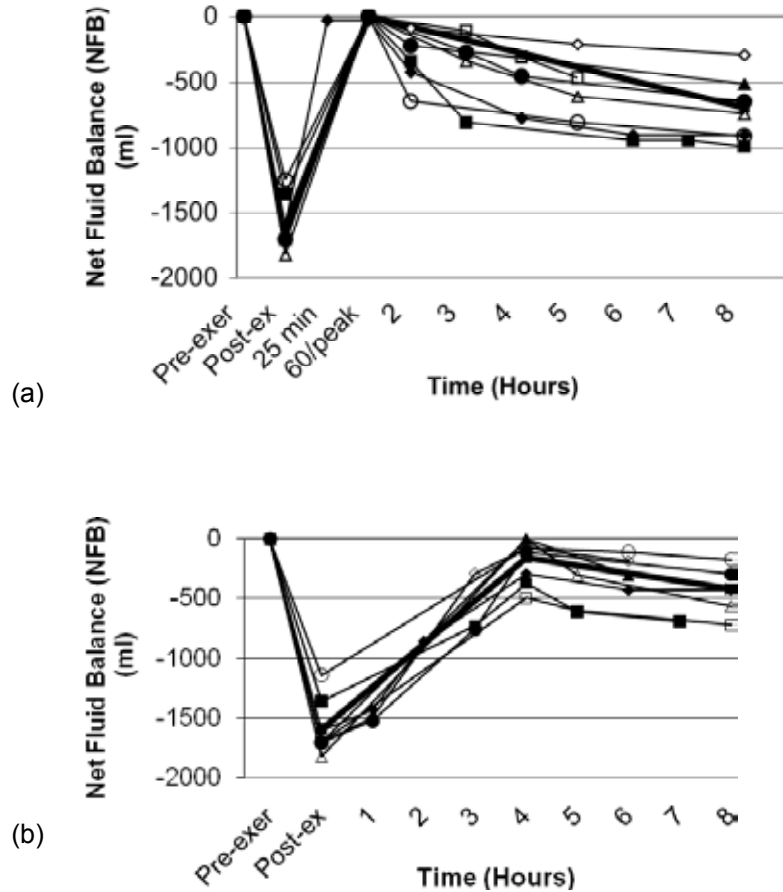


Figure 1 — Net fluid balance (NFB) over time for each participant recovering from dehydration to 2% of body weight and rehydrated with (a) bolus water consumption and (b) metered water consumption. Each line represents individual participant data. Mean NFB is represented by the bold line.

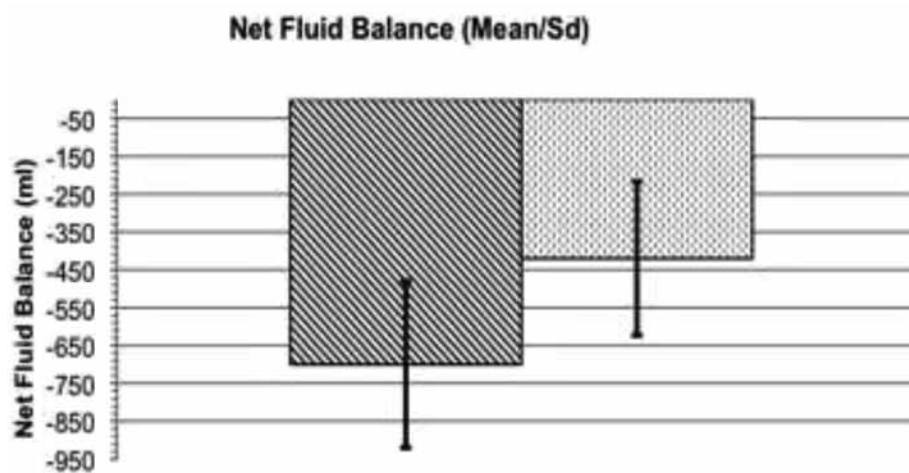


Figure 2 — Net fluid balance for bolus and metered trials over 8-hr collection.

appears to cause rapid changes in both volume and osmolality of blood (Verney, 1946). Rapid changes in blood osmolality decrease the secretion of the antidiuretic hormone vasopressin and aldosterone, which creates a water diuresis response by the kidney through less retention of Na⁺ (Nose, Mack, Shi, & Nadel, 1988a; Verney, 1946). Blood-volume increases have a similar response in that increases in central venous pressure are detected by the kidneys and result in less secretion of vasopressin and aldosterone, causing additional diuresis (Gauer & Henry, 1963). During periods of hypohydration, selective restoration and maintenance of blood volume and osmolality with a given fluid consumed override replacement of fluids intracellularly, thereby increasing urine production and diminishing rehydration (Nose, Mack, Shi, & Nadel, 1988b; Stachenfeld et al., 1996). We postulate that overcompensation of the kidneys when confronted with a large bolus of fluid is similar to that of insulin's hypersensitive response to a large bolus of sugar and the concomitant drop in blood glucose.

A similar study by Kovacs et al. (2002) using a high versus low rate of ingestion with a carbohydrate-electrolyte beverage found no significant difference between urine output during a 6-hr recovery period. Unlike the current study, hydration efficiency was relatively unaffected by varying ingestion rates ($3\% \pm 5\%$ between trials). The difference in findings between Kovacs et al.'s and the current study may be a result of two major differences. First, Kovacs et al. used a carbohydrate-electrolyte beverage whereas we used water. In unpublished work in our laboratory we have found that a carbohydrate-electrolyte beverage acts differently than water under these circumstances. Second, Kovacs et al. used two similar ingestion rates. A high rate of consumption in Kovacs et al.'s study consisted of administering fluids over a period of 3 hr as compared with 5 hr in the low-rate group. When compared with the current study (4-hr metered ingestion), the high ingestion rate used by Kovacs et al. was similar to our metered approach.

Many studies have addressed the volume of fluids needed to reach a euhydrated state postexercise. Although fluid-volume studies have helped elucidate some of the issues concerning total rehydration after exercise-induced dehydration, much of this research has focused on positive NFB during recovery rather than practical rehydration strategies (Galloway, 1999). Several previous studies have reported that a 150% volume of ingestion is most effective in achieving euhydration over a short period of time (Maughan et al., 1997; Shirreffs & Maughan, 2000). Although the current study only used a 100% volume of ingestion, we agree with this previous work, because none of our participants reached a euhydrated state while consuming just 100% of fluids lost. However, it is interesting to note that by manipulating the rate of administration, NFB was actually higher in the metered trial consuming 100% in our study than with the 150% bolus consumption in previous studies (Maughan & Leiper, 1995; Shirreffs & Maughan, 1998). NFB describes the level of hydration at the end of trials independent of insensible

losses (transepidermal, respiratory, and fecal), which were not accounted for in either the current study or the aforementioned studies. In the current study, insensible fluid losses would be expected to be similar for both treatments. Practically speaking, insensible fluid losses are unavoidable and would be expected to reduce hydration efficiency slightly in all cases, whether in the field or in the laboratory.

Hydration efficiency concerns the amount of fluid retained versus fluid lost to urine. The final NFB for metered consumption in the current study was -420 ml compared with -689 ml and -642 ml in the 150% bolus trials (Maughan & Leiper, 1995; Shirreffs & Maughan, 1998). These data suggest that a metered fluid-administration technique may be more effective than administering larger volumes of fluid to achieve euhydration. This greater NFB was maintained for longer periods; the current study monitored fluid balance for 8 hr compared with 6 hr in the aforementioned studies (see Figure 1). In regard to these comparisons, it is important to note that unlike the aforementioned studies, the current study provided small amounts of food, in the form of two small meals, to participants during data collection, thereby supplying Na⁺ (820 mg) and additional water (116 ml) during rehydration. However, in application, people would be expected to take in some food in similar situations.

Another possible benefit of this type of fluid administration is the practical aspect of mimicking a more typical style of fluid consumption. The voluntary impetus to drink will probably not lend itself to consumption of large volumes of fluid (*ad libitum*) over short periods of time (<2 hr). Several participants in the current study expressed discomfort during bolus consumption when 100% of water loss replacement was ingested. Greater volumes would be expected to magnify acute gastrointestinal discomfort during consumption. In addition, gastric-emptying rates have been shown to increase with exposure to larger volumes of fluid (Mitchell et al., 1994; Noakes, Rehrer, & Maughan, 1991). Adaptations to gastric-emptying rates with increased volumes of fluid have been interpreted as advantageous for rehydration. However, slower rates of gastric emptying may mitigate the endocrine response of the kidneys, thereby minimizing urine loss.

Finally, previous work in this area has addressed rehydration in situations in which the amount of fluids is unlimited. When an unlimited fluid volume is available, our results may be of lesser practical value, because regardless of the volume of fluid lost to urine production, additional fluids could be consumed. However, in survival situations, wildland firefighting, or military missions, in which fluid supplies are limited, it appears that the way fluid is consumed may greatly increase hydration efficiency when fluid volumes are limited. Increasing hydration efficiency when the amount of fluid available is limited would maintain body-fluid levels for longer periods of time and may sustain physical performance, as well, thereby enhancing performance and survival.

In summary, it appears from these data that the way fluids are administered may increase fluid retention over time. This style of drinking may also increase drinking adherence because of reduced gastric discomfort and prove most beneficial in situations in which rehydration fluid volumes must be conserved.

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