International Journal of Sport Nutrition and Exercise Metabolism, 2011, 21, 480-491

Unilateral Fluid Absorption and Effects on Peak Power After Ingestion of Commercially Available Hypotonic, Isotonic, and Hypertonic Sports Drinks

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Isotonic sports drinks are often consumed to offset the effects of dehydration and improve endurance performance, but hypotonic drinks may be more advantageous. The purpose of the study was to compare absorption and effects on performance of a commercially available hypotonic sports drink (Mizone Rapid: 3.9% carbohydrate [CHO], 218 mOsmol/kg) with those of an isotonic drink (PowerAde: 7.6% CHO, 281 mOsmol/kg), a hypertonic drink (Gatorade: 6% CHO, 327 mOsmol/kg), and a noncaloric placebo (8 mOsmol/kg). In a crossover, 11 cyclists consumed each drink on separate days at 250 ml/15 min during a 2-hr preload ride at 55% peak power followed by an incremental test to exhaustion. Small to moderate increases in deuterium oxide enrichment in the preload were observed with Mizone Rapid relative to PowerAde, Gatorade, and placebo (differences of 88, 45, and 42 parts per million, respectively; 90% confidence limits ±28). Serum osmolality was moderately lower with Mizone Rapid than with PowerAde and Gatorade (–1.9, –2.4; mOsmol/L; ±1.2 mOsmol/L) but not clearly different vs. placebo. Plasma volume reduction was small to moderate with Mizone Rapid, PowerAde, and Gatorade relative to placebo (–1.9%, –2.5%, –2.9%; ± 2.5%). Gut comfort was highest with Mizone Rapid but clearly different (8.4% ± 4.8%) only vs PowerAde. Peak power was highest with Mizone Rapid (380 W) vs. placebo and other drinks (1.2–3.0%; 99% confidence limits ±4.7%), but differences were inconclusive with reference to the smallest important effect (~1.2%). The outcomes are consistent with fastest fluid absorption with the hypotonic sports drink. Further research should determine whether the effect has a meaningful impact on performance.

Keywords*:* deuterium oxide, carbohydrate-electrolyte solutions, carbohydrate, osmolality

During prolonged endurance exercise, there can be sufficient depletion of muscle and liver glycogen and evaporative loss of body fluid to negatively affect endurance performance (Gisolfi & Duchman, 1992; Maughan, Bethell, & Leiper, 1996). Athletes and other individuals undertaking prolonged exercise are therefore encouraged to ingest solutions containing carbohydrate and electrolytes during exercise (Gisolfi & Duchman, 1992). The ingested fluid and carbohydrate can independently enhance endurance performance (Maughan et al., 1996), but functional limits for each are evident with gastric emptying progressively delayed by increasing carbohydrate and osmolar concentrations (Costill & Saltin, 1974; Murray, Bartoli, Eddy, & Horn, 1997; Murray, Bartoli, Stofan, Horn, & Eddy, 1999) and with low drink volume (Mitchell & Voss, 1991).

Whether differences in endurance performance of a worthwhile magnitude can result from manipulation of ingestion rate, osmolality, formulation, and concentration of carbohydrate in an oral rehydration solution remains to be established. Mindful of optimizing fluid delivery, several review authors have concluded that solutions comprising 40–80 g/L of glucose polymers and mono- and disaccharides with 10–30 mEq/L Na^+ falling in the hypoisotonic range are likely to optimize gastric emptying and intestinal fluid absorption while containing sufficient carbohydrate to benefit performance over water alone (Brouns & Kovacs, 1997; Coombes & Hamilton, 2000; Gisolfi & Duchman, 1992; Leiper, 1998). Most commercially available sports drinks fall within these guidelines (see, e.g., Brouns & Kovacs, 1997; Coombes & Hamilton, 2000), but most are formulated with a high percentage of monosaccharides for consumer sweetness preference, which may delay absorption by pushing solution osmolality into the isotonic to hypertonic range. Delayed absorption might also cause gastrointestinal distress (Shi et al., 2004), and there is a relationship between even mild gastrointestinal distress and impaired endurance performance (Davis, Burgess, Slentz, Bartoli, & Pate, 1988; Shi et al., 2004). In his review, Leiper suggested that the small differences in osmolality and carbohydrate content found within the commercial range may have a meaningful influence on fluid absorption and performance.

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These considerations contributed to the decision of a drink manufacturer (Frucor Beverages, NZ) to formulate a hypotonic sports drink, and we were approached to compare its rate of absorption and its effects on performance with those of water and other popular sports drinks. We found only two relevant previous studies of absorption and performance that included a hypotonic drink, and neither produced decisive outcomes. Maughan et al. (1996) compared the effects of ingestion of nonblinded water and isotonic (310 mOsmol/kg) and hypotonic (240 mOsmol/kg) glucose-sodium solution on cycling endurance in healthy men. Times were longer by 9–18% for either solution than for water, but the comparison of the two solutions was unclear. The decline in plasma volume was least with the hypotonic solution. In a later study, exercise capacity in 6 healthy men in a hot environment was 40% longer with a hypotonic glucose-sodium solution (2% carbohydrate, 239 mOsmol/kg) than with a mildly hypertonic sucrose-electrolyte solution (15% carbohydrate, 324 mOsmol/kg; Galloway & Maughan, 2000). In addition, heart rate was 7 beats/min lower and there was 2–9% attenuation in the decline in plasma volume with the 2% versus 15% carbohydrate solution, suggesting that a substantial improvement in stroke volume and cardiovascular function might have contributed to the substantial improvement in performance with the hypotonic drink. Nonetheless, the difference in performance could not be ascribed simply to the difference in tonicity or carbohydrate dose, because the hypotonic drink was consumed at approximately twice the rate of the other drink.

To investigate the effects of drink tonicity on fluid absorption and performance, we used a new hypotonic drink (Mizone Rapid) and compared it with isotonic (PowerAde), mildly hypertonic (Gatorade), and strongly hypotonic (water placebo) solutions. We hypothesized that unilateral fluid absorption estimated from appearance of plasma deuterium oxide (D_2O) would be greatest with the hypotonic solution and water and that this would transpire to a small enhancement in high-intensity endurance performance.

Methods

Subjects

Eleven well-trained male cyclists and triathletes age 29 ± 8 years (*M* ± *SD*) with a body mass of 73.9 ± 9.1 kg participated in the study. Maximum oxygen uptake (VO_{2max}) and power (W_{max}) were 4.6 ± 0.5 L/min and 378 ± 43 W, respectively, and cyclists completed on average 16.5 ± 4.4 hr/week of training. Cyclists were screened for contraindications assessed by a general health questionnaire and gave written consent to participate in accordance with the protocol approved by the AUT University ethics committee.

Sample size was dictated by availability of subjects and resources to investigate them. With a smallest worthwhile change of 0.3× within-subject *SD* (see Statistical Analysis), a sample size of 62 is needed for a null effect on a performance-dependent variable to be clinically clear (Hopkins, 2006). Our final sample size of 11 would give clear outcomes for small effects (at least 0.6 of the within-subject *SD*).

Experimental Design

The design was a double-blind Latin-square randomized crossover. Each cyclist visited the laboratory on six occasions over a 5-week period. Visit 1 comprised measurement of body mass and height, VO_{2max}, and W_{max}. On a following day, a full familiarization trial of the exercise protocol was completed. On Visits 3–6, cyclists ingested a different commercial sports drink or flavored placebo during the 2-hr ride. Cyclists completed food and fluid intake records for the complete day before the first testing session; the exact food and fluid intake was then replicated before subsequent testing days by means of a checklist that was cross-checked by the researchers. Training intensity and volume were recorded for 7 days before the start of the first experimental testing day, with standardization from the first immediate 2 days before each performance test that included a day off training before the experimental tests days. To promote euhydration, each cyclist was provided with and asked to consume 2.5 L of bottled water throughout the day before each testing session to meet the 3-L resting daily water requirement including ~1 L from food (Sawka, Cheuvront, & Carter, 2005). On the day of testing, cyclists were not allowed to undertake any deliberate training or exercise including cycling or walking to the research laboratory. This requirement was to reduce the variation in preexercise hematology caused by exercise-induced fluid shifts (Dill & Costill, 1974). For any given cyclist, all laboratory tests were conducted at the same time of day to control for circadian variance.

Preliminary Testing and Familiarization

VO_{2max} and W_{max} were determined via an incremental exercise test on a cycle ergometer (Velotron, Racermate, Seattle, WA). The test commenced at a workload of 150 W, increasing 30 W every 3 min until volitional exhaustion. VO_2 was measured continuously using a metabolic cart (Metamax 3b, Cortex, Leipzig, Germany), and VO_{2max} was determined as the highest 30-s value obtained during the test. W_{max} was defined as the last completed work rate plus the fraction of time spent in the final uncompleted work rate multiplied by the work-rate increase. The familiarization trial of the exercise protocol comprised a 2-hr constant-workload ride at 55% W_{max} followed by an incremental exercise test to exhaustion as a measure of endurance peak power. The ride was paused for 5 min at 1 hr and at completion of the 2 hr for urine collection and body-mass measurement. The incremental test commenced at 180 W and increased by 1 W/2 s until volitional exhaustion. Cyclists were blind to elapsed time, cadence, power output, and heart rate during the test. Exhaustion was determined as the point when cadence could not be maintained above 70 rpm after two verbal warnings from the researchers. A fan was used for cooling.

Main Trial

On reporting to the laboratory, participants were provided with a preexercise meal comprising a cereal bar (carbohydrate 19.7 g, fat 8.6 g, protein 2.5 g) and 250 ml of water, after which they remained seated in the cycling position to permit equilibration of plasma volume. Thirty-five minutes later a 20GA cannula with two-way stopcock valve (Becton Dickinson Medical Pte. Ltd., Singapore) was inserted into the antecubital vein for serial blood sampling. At all times the cannula was maintained patent by flushing with sterile saline (Becton Dickinson Medical). Thereafter, preexercise urine and blood samples were collected, and cyclists consumed 250 ml of test drink before beginning the exercise procedure (Figure 1). During exercise, 3-ml blood samples were drawn every 20 min for analysis of hematocrit, as well as hemoglobin and glucose concentration. Further 3-ml blood samples were drawn at 14 and 74 min (for background plasma D_2O enrichment) and at 17, 20, 25, 30, 40, 50, 60, 77, 80, 85, 90, 100, 110, and 120 min of exercise. Perceived exertion and gut comfort were measured every 20 min on a Likert scale with sampling 1 min before the ingestion of each drink bolus. Ten-second average heart rate was obtained every 5 min during the 2-hr ride (Polar A1, Polar Electro, Kempele, Finland). Drink servings of 250 ml were consumed at exactly 15-min intervals throughout the 2-hr ride. Five grams of D_2O (99.8%, Cambridge Stable Isotopes, Andover, MA) were added to the second bolus (ingestion time 15 min) and the sixth bolus (ingestion time 75 min). Cyclists consumed all drinks within 10–15 s of receiving them, with the residual taken up via a straw. Environmental conditions were maintained with air conditioning at 19–21 °C and 50–60% relative humidity.

Drinks

The three commercial beverages tested were the hypotonic solution (Mizone Rapid, Frucor Beverages, Auckland, New Zealand: 3.9% carbohydrate, 8 mmol/L Na^+, 220 mOsmol/kg), the isotonic solution (PowerAde, Coca-Cola Amatil, Auckland, NZ: 7.6% carbohydrate, 12 mmol/L Na^+, 281 mOsmol/kg), and the hypertonic solution (Gatorade, Schweppes Australia Pty. Ltd., Sydney, NSW: 6% carbohydrate, 21 mmol/L Na^+, 327 mOsmol/kg). These were compared with a placebo comprising artificially sweetened water (Na^+ not measured) of flavor (orange) identical to that of the test solutions with osmolality of 10 mOsmol/kg. Osmolality was measured on five occasions during the 5-month study to trace any change resulting from carbohydrate hydrolysis: *SD*s of the means presented above were 1.5, 1.9, 2.6, and 1.3 mOsmol/kg, respectively. Solution parameters were measured by the third party who also held the blinding code. All the four test solutions were made up in one batch each, transferred into identical 250-ml glass bottles covered with an opaque sleeve, and stored refrigerated at ~8 °C before consumption. Evaluated via oral questioning, neither the cyclists nor the experimenters were able to identify the solution identity, that is, tonicity, carbohydrate concentration, brand, or placebo.

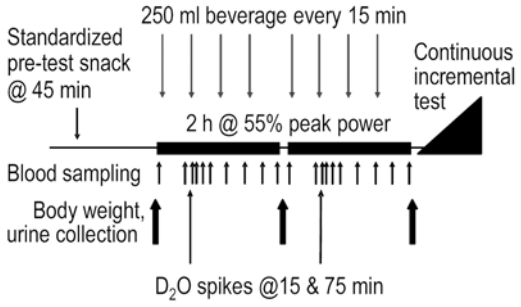

Figure 1 — Experimental protocol performed on the Velotron cycle ergometer.

Analyses

Blood was transferred into prechilled lithium heparin Vacutainers and stored on ice and to untreated Vacutainers and stored at room temperature (Becton Dickinson & Co., Franklin Lakes, NJ). Hemoglobin concentration (Bayer Rapidlab 800, Bayer HealthCare LLC, Tarrytown, NY) and hematocrit (microcentrifugation) were analyzed for hemodynamic evaluation (Δ blood, red cell, and plasma volume) using the method of Dill and Costill (1974). Remaining blood was centrifuged at 2,000 *g*, 4 °C for 12 min and the resulting plasma aspirated into Eppendorf tubes and stored at –80 °C until later for analysis of plasma glucose and Na^+ concentration (Bayer Rapidlab 800), while osmolality was determined in the plasma by freeze-point depression.

Plasma D_2O enrichment was determined by continuous-flow isotope ratio mass spectrometry (Europa Scientific ANCA-GSL and GEO 20–20 IRMS, Crewe, UK). The relative absorption of water into the circulation was initially to be determined using the method of Hill, Bluck, and Davies (2004), but we thought that the use of the concentration of D_2O label in blood to model the rate of fluid uptake required too many unjustified assumptions about compartment volumes, bidirectional flux, and rates of disappearance of the label. Instead, unilateral fluid absorption was qualified as the absolute difference in enrichment across the sampling points.

Statistical Analysis

Data were analyzed using mixed linear modeling (SAS Version 9.2, SAS Institute, Cary, NC). The fixed-effects model included terms to adjust for the trial number of the treatment (learning or fatigue effects) and the effects of the within-subject covariates ambient temperature and the log of pretest urine osmolality (which were linearly rescaled to a mean of zero for each subject). In addition to the between-subjects and residual variance, the random-effects model included a term representing additional error on the first trial. Peak power in the incremental test was analyzed after log transformation to reduce nonuniformity of effects and error; other dependent variables

were analyzed untransformed. Models for variables with multiple observations on each test day included an additional fixed and random effect for the repeated measurements.

Uncertainty arising from sampling variation was dealt with as probabilistic inferences based on important magnitudes for clinical effects (on performance) and mechanistic effects (on all other dependent variables), as described elsewhere. The magnitudes of effects on performance were decided via a novel rationale (Bonetti & Hopkins, 2010): The performance test was assumed to simulate the physical demands of an extended sprint to the finish in a road race, and therefore the threshold for smallest important change in performance was 0.3× within-subject variation, and those for moderate and large effects were 0.9× and 1.6× within-subject variation (Hopkins, Marshall, Batterham, & Hanin, 2009). The magnitudes of effects on other variables were set via standardization with the between-subjects standard deviation derived from the mixed linear model: thresholds of 0.2, 0.6, and 1.2 *SD* for small, moderate, and large (Hopkins et al., 2009). Uncertainty in effects is shown as 99% confidence limits for performance and 90% confidence limits for other variables.

Results

2-hr Ride

Figure 2 shows the most important measures relating to fluid absorption, which also happened to be those with the biggest differences between the drinks. The comparisons of Mizone Rapid with the other drinks on plasma D_2O enrichment are summarized in Table 1. Enrichment

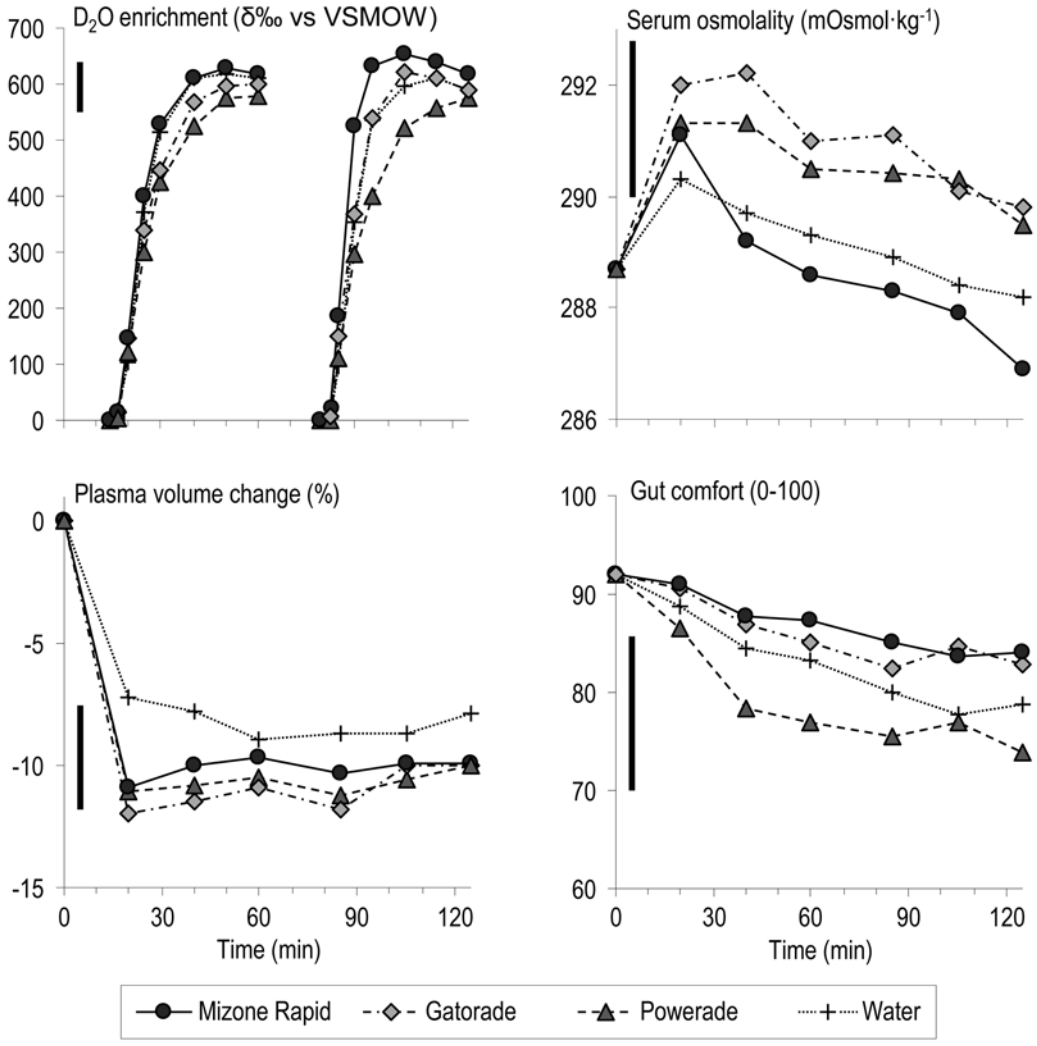

Figure 2 — Uptake of D_2O label, serum osmolality, plasma volume change, and gut comfort during the 2-hr ride. Data are least-squares means. Bars are the mean *SD* (typical difference between subjects at any given time point). The D_2O enrichment is the concentration above the background level measured immediately before consuming the drink bolus containing the label. VSMOW = Vienna standard mean ocean water. Statistical differences are presented in Tables 1 and 2.

Table 1 Statistical Summary of the Effect of Drink Composition on Mean Plasma Deuterium Oxide Enrichment During the 2-hr Ride

	Mean Enrichment[a] (δ% vs. VSMOW)					Effect Comparison Between Drinks[b]							
Time	Mizone Rapid	PowerAde	Gatorade	Water	*SD*[c]	Mizone Rapid–PowerAde	Mizone Rapid–Gatorade	PowerAde–Gatorade	Mizone Rapid–water	PowerAde–water	Gatorade–water	90% CL	Threshold[d]
15–60 min	420	362	387	407	88	58, moderate ↑ m. likely	33, small ↑ likely	–25, small ↓ possible	14, possibly trivial	–45, small ↓ v. likely	–20, small ↓ possible	±24	18
75–120 min	469	352	412	399	99	117, moderate ↑ m. likely	57, small ↑ likely	–60, small ↓ likely	70, moderate ↑ v. likely	–47, small ↓ likely	13, unclear	±42	20
Overall	444	357	399	402	94	88, moderate ↑ m. likely	45, small ↑ likely	–43, small ↓ likely	42, small ↑ likely	–46, small ↓ likely	–3, unclear	±28	19

Note. VSMOW = Vienna standard mean ocean water; ↑ = increase; m. = almost certainly; ↓ = decrease; v. = very.

[a]Least-squares means of raw measures. [b]Effect comparisons are expressed as unit change from the reference condition with the associated qualifying effect magnitude and statement of likelihood of a substantial (small or greater) effect. Qualified thresholds for standardized change: 0–0.2 trivial, 0.2–0.6 small, 0.6–1.2 moderate, 1.2–2.0 large, 2.0–4.0 very large. Threshold for probability of a substantial effect: <1.0% almost certainly not, 1.0–5% very unlikely, 5–25% unlikely, 25–75% possible, 75–95% likely, 95–99% very likely, >99% almost certain, where an effect is unclear if its confidence interval includes both substantial increases and decreases. [c]Typical variation between subjects derived from a linear model. [d]Threshold for small effect is the traditional Cohen effect size 0.2× between-subjects *SD*, adjusted for small-sample bias.

was highest with Mizone Rapid, the differences being larger in the second hour of the ride. Serum osmolality was moderately lower with Mizone Rapid than with PowerAde and Gatorade. Placebo produced the least drop in plasma volume; differences between the sports drinks were trivial but unclear. Gut comfort showed the smallest decline with Mizone Rapid, but the difference compared with Gatorade was unclear and the observed difference was only trivial.

Data for the other measures taken during the 2-hr ride (Figure 3) and a statistical summary (Table 2) are provided. The only noteworthy effects were as follows: clearly lowest blood glucose with placebo and highest with PowerAde; lowest (first half) heart rate with Mizone Rapid and placebo, but differences between Mizone Rapid and the other drinks were trivial (0.6–1.8/min); trivial differences between all drinks for perceived exertion (not shown); and higher plasma Na^+ (0.6–1.1 mMol/L) with Gatorade than with the other drinks and placebo. Finally, urine osmolality was lowest with placebo (274 mOsmol/kg), but differences between the sports drinks were unclear (vs. PowerAde, Mizone Rapid, and Gatorade: 56, 41, 34; 90%CL ± 26–42, respectively).

Performance Test

The within-subject standard deviation from test to test derived from the mixed model was 3.9% (15 W); thresholds for small, moderate, and large effects were therefore 1.2%, 3.5%, and 6.2%. Ambient temperature and pretest urine osmolality had clear small detrimental effects on performance (effects of 2 *SD:* –3.0% and –2.8%, respectively; 99%CL ±2.9%). There was no additional error on the first trial, and there was a clear steady decline in performance between trials, reaching a moderate effect of 5.7% (99%CL ± 5.0%) between the first and last trials. After adjustment for these effects in the mixed model, least-squares mean peak powers reached in the incremental test after the 2-hr ride were as follows: Mizone Rapid, 380 W; PowerAde, 376 W; Gatorade, 376 W; placebo, 369 W; between-subjects *SD*, 13% (47 W). The percentage differences between Mizone

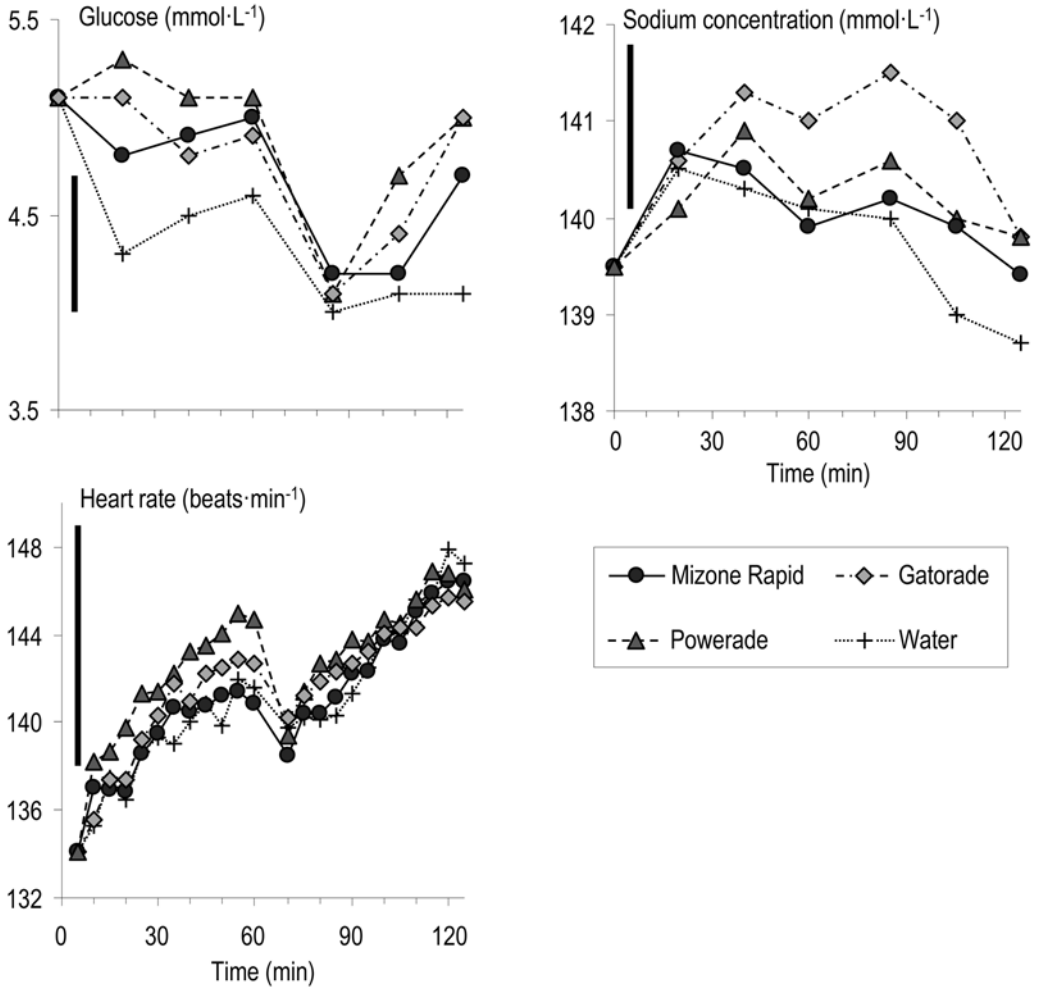

Figure 3 — Blood glucose and sodium concentration and heart rate during the 2-hr ride. Data are least-squares means. Bars are the mean *SD* (typical difference between subjects at any given time point). Statistical differences are presented in Table 2.

Table 2 Statistical Summary of the Effect of Drink Composition on Physiological and Perceptual Measures During the 2-hr Ride

	Mean Effects[a]					Effect Comparison Between Drinks[b]							
Measure	Mizone Rapid	PowerAde	Gatorade	Water	*SD*[c]	Mizone Rapid–PowerAde	Mizone Rapid–Gatorade	PowerAde–Gatorade	Mizone Rapid–water	PowerAde–water	Gatorade–water	90% CL	Threshold[d]
Gut comfort (0–100)	87	78	85	85	16	8.4, small ↑ v. likely	1.1, unclear	–7.4, small ↓ likely	4.3, small ↑ possible	–4.1, small ↓ possible	3.3, small ↑ possible	4.8	3.3
RPE (0–100)	50	51	50	50	14	–1.3, unclear	–0.1, unclear	1.2, unclear	–0.3, unclear	1.0, unclear	–0.2, unclear	5.5–5.8	3.0
Heart rate (beats/min)	141	143	142	141	11	–1.8, possible trivial	–0.6, likely trivial	1.2, likely trivial	0.0, unclear	1.8, possibly trivial	0.6, likely trivial	2.3–2.8	2.3
Blood glucose (mmol/L)	4.7	4.9	4.7	4.3	0.7	–0.22, small ↓ possible	–0.03, unclear	0.19, small ↑ possible	0.40, small ↑ possible	0.61, moderate ↑ m. likely	0.43, moderate ↑ v. likely	0.27	0.13
Serum osmolality (mOsmol/L)	288.7	290.6	291	289.2	2.8	–1.9, moderate ↓ v. likely	–2.4, moderate ↓ v. likely	–0.5, unclear	–0.5, unclear	1.4, small ↑ likely	1.9, moderate ↑ v. likely	1.2	0.6
Change in plasma volume (%)	–10.1	–10.7	–11	–8.2	4.3	0.6, unclear	0.9, unclear	0.4, unclear	–1.9, small ↓ possible	–2.5, small ↓ likely	–2.9, moderate ↓ likely	2.5	0.9
Sodium (mmol/L)	140.1	140.3	140.9	139.8	1.7	–0.2, unclear	–0.8, small ↓ likely	–0.6, small ↓ likely	0.3, unclear	0.5, unclear	1.1, moderate ↑ likely	0.5	0.3
Urine osmolality (mOsmol/L)	349	386	331	247	202	–9.5, unclear	5.5, unclear	16.6, possibly trivial	41.3, small ↑ likely	56.1, small ↑ v. likely	33.9, likely trivial	26–42	13.1
Urine volume (ml)	281	188	275	271	271	49.2, likely trivial	2.2, unclear	–31.6, possibly trivial	3.8, unclear	–30.5, possibly trivial	1.6, unclear	50–73	21.1

Note. ↑ = increase; v. = very; ↓ = decrease; RPE = rating of perceived exertion; m. = almost certainly.

[a]Least-squares means of raw measures. Data are the overall mean effect for the 2-hr ride. Any noteworthy divergence from the overall trend is presented in the text. [b]Effect comparisons are expressed as unit change from the reference condition with the associated qualifying effect magnitude and statement of likelihood of a substantial (small or greater) effect. Qualified thresholds for standardized change: 0–0.2 trivial, 0.2–0.6 small, 0.6–1.2 moderate, 1.2–2.0 large, 2.0–4.0 very large. Threshold for probability of a substantial effect: <1.0% almost certainly not, 1.0–5% very unlikely, 5–25% unlikely, 25–75% possible, 75–95% likely, 95–99% very likely, >99% almost certain, where an effect is unclear if its confidence interval includes both substantial increases and decreases. [c]Typical variation between subjects derived from a linear model. [d]Threshold for small effect is the traditional Cohen effect size 0.2× between-subjects *SD*, adjusted for small-sample bias.

Rapid and the other drinks are shown in Figure 4. None of the differences between Mizone Rapid and the other drinks were clear, although the observed differences were possible small benefits in favor of Mizone Rapid (likelihoods harm/benefit: Mizone rapid vs. PowerAde 8/50, vs. Gatorade 8/52, vs. placebo 1.1/84.2). There were no clear differences in the maximum heart rate or peak lactate concentration reached between the drinks (data not shown).

Discussion

In our study we compared the effects of hypotonic, isotonic, and mildly hypertonic sports drinks and placebo on fluid absorption, hydration-sensitive physiological parameters, and endurance peak power. Analysis of plasma D_2O enrichment suggests moderately higher unilateral fluid absorption with the hypotonic (Mizone Rapid) followed equally by the hypertonic (Gatorade) and placebo solutions, and finally by the isotonic (PowerAde) sports drink. Serum osmolality was lowest with Mizone Rapid relative to the other sports drinks and not clearly different from that with placebo; in contrast, osmolality was increased with Gatorade and PowerAde relative to placebo. In addition, gut comfort rating over the 2-hr ride was reduced the least with Mizone Rapid but similar relative to Gatorade, and only the difference relative to PowerAde was substantial. We observed a possible small benefit on peak power with Mizone Rapid relative to placebo, but none of the other differences were clear.

Our evidence for faster fluid absorption with Mizone Rapid is consistent with most previous intubation-based observations of faster intestinal water absorption with hypotonic oral rehydration solutions than with more concentrated solutions (Hunt, Elliott, Fairclough, Clark, & Farthing, 1992; Hunt, Elliott, & Farthing, 1989; Leiper, 1998; Leiper, Davidson, & Maughan, 1991; Rolston, Zinzuvadia, & Mathan, 1990; Thillainayagam, Carnaby, Dias, Clark, & Farthing, 1993). In solutions similar to those of the current study, Leiper et al. (1991) demonstrated median jejunal fluid-absorption rates of 8.2, 6.1, and 3.2 ml $\cdot$ cm^{-1} $\cdot$ hr^{-1} using the triple-lumen technique with a hypotonic (240 mOsmol/kg) and two mildly hypertonic (312, 336 mOsmol/kg) solutions in resting males; solution carbohydrate concentrations were 17.8, 40.0, and 48.9 g/L, respectively. In a subsequent report, holding total carbohydrate (332 mmol/glucosyl unit) and sodium concentration (21 mmol/L) of the perfused solutions constant but varying osmolality (229–352 mOsmol/kg), net water absorption was 2.0- and 3.8-fold faster from the most hypotonic solution than with the isotonic (282 mOsmol/kg) and hypertonic solutions (352 mOsmol/kg), respectively (Leiper, Brouns, & Maughan, 1994). Rolston et al. also reported fastest water absorption with a 177-mOsmol/kg solution than with higher concentrations (219–335 mOsmol/kg). However, others have reported faster water absorption with an isotonic solution relative to distilled water (Gisolfi, Summers, Schedl, Bleiler, & Oppliger, 1990) or no significant difference with a range of solutions containing multiple transportable carbohydrates (186–417 mOsmol/kg) compared with water (Gisolfi, Summers, Lambert, & Xia, 1998; Shi, Summers, Schedl, Chang, Lambert, & Gisolfi, 1994). In an underpowered study, Rogers, Summers, and Lambert (2005) reported no significant difference in intestinal fluid absorption between water and 3% (159 mOsmol/kg) and 6% (280 mOsmol/kg) glucose-salt solutions.

Although some differences between individual studies remain that might be explained in part by differences in total solute and carbohydrate composition, Shi and Passe (2010) concluded by statistical metaregression that overall osmolality plays a significant role in water absorption in the duodenojejunum. They found that solutions containing single carbohydrates have a higher negative correlation with water absorption than solutions

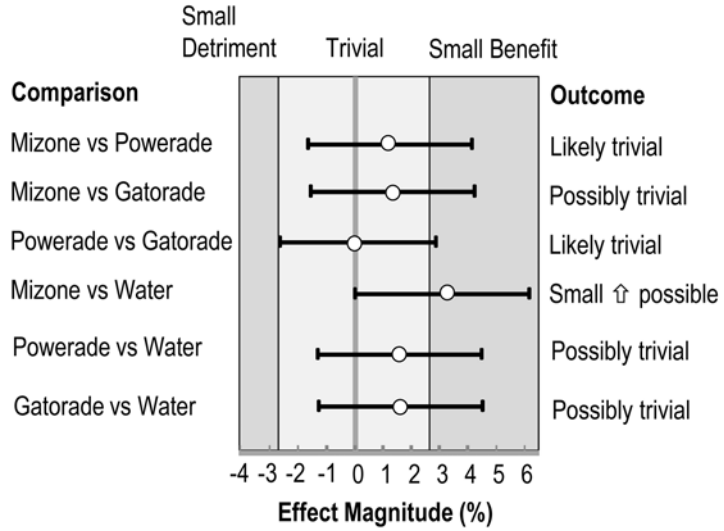

Figure 4 — Comparison of peak power in the incremental test after consumption of the three sports drinks and placebo. Bars are 99% confidence intervals.

containing multiple transportable carbohydrates (e.g., glucose, fructose, sucrose) and that this effect is greatest in the jejunum, with the negative correlation disappearing. Because duodenojejunal water absorption is correlated with carbohydrate absorption (Shi & Passe, 2010; Shi, Summers, Schedl, Flanagan, Chang, & Gisolfi, 1995), carbohydrate blends that are transported faster will also promote faster water absorption. For example, Jentjens et al. (2006) reported higher plasma D_2O accumulation with the ingestion of glucose and fructose (2:1 ratio) than with the ingestion of isocaloric glucose only. Indeed, the higher D_2O enrichment and improved gut comfort with Gatorade compared with PowerAde in the current study suggest that differences in carbohydrate concentration or composition between the two drinks could have sufficient influence on fluid absorption to override the impact of osmolality. Unfortunately, we are unable to comment further on carbohydrate composition of the test beverages, because the fractional proportions of fructose, glucose, sucrose, and maltodextrin are not in the public domain.

Although the osmolality of solutions over the range tested appears to have only a minor influence on the rate of gastric emptying (Brouns, Senden, Beckers, & Saris, 1995; Shi & Passe, 2010), hypotonicity creates a favorable osmotic gradient in the proximal small intestine that allows the high permeability of the duodenojejunum to be rapidly and fully used in fluid absorption (Gisolfi, Patrick Lambert, & Summers, 2001). In addition, segmental membrane properties could have played an important role in the D_2O outcome. Intestinal permeability decreases from the jejunum to the ileum (Fordtrain, Rector, Ewton, Soter, & Kinney, 1965), but the jejunum has more carbohydrate transporters that drive or facilitate carbohydrate, electrolyte, and water absorption (Lambert, Chang, Xia, Summers, & Gisolfi, 1997). These structural characteristics may help explain the higher D_2O enrichment with Mizone Rapid than with the other more concentrated drinks, simply because the fluid in Mizone Rapid was able to be absorbed earlier in the most proximal segment before reaching the jejunum, where carbohydrate and water absorption rates presumably increased because of a higher concentration of sugar transporters.

We present evidence from multiple markers (e.g., lowest plasma D_2O accumulation and gut comfort, highest first-half heart rate) to suggest that PowerAde is absorbed more slowly than the other sports drinks and placebo. At 280 mOsmol/kg, PowerAde is isotonic to body fluids when ingested but 50 mOsmol/kg lower than Gatorade, which had higher D_2O accumulation. Carbohydrate concentration is negatively correlated with water absorption in the proximal small intestine (Jeukendrup, Currell, Clarke, Cole, & Blannin, 2009; Shi & Passe, 2010), so it is possible that the higher carbohydrate concentration (7.6%) than both Gatorade (6%) and Mizone Rapid (3.9%), rather than osmolality, could account for the lower apparent rate of net fluid absorption. Unilateral D_2O absorption is an integrated measure of gastric emptying and intestinal absorption, so although the high concentration could slow intestinal absorption, lower D_2O accumulation could also be caused by slower gastric emptying. Intubation data show that an 8% glucose-fructose-maltodextrin solution was emptied on average significantly more slowly (9.1 ml/min) during 90-min exercise than a 6% glucose-fructose solution (11.0 ml/min; Murray et al., 1999). In addition, although ingested osmolality was 280, an increase after hydrolysis of the sucrose and maltodextrin at the brush-border membrane would have substantially increased effective luminal osmolality, possibly inducing a negative-feedback loop, further slowing gastric emptying (Meeroff, Go, & Phillips, 1975).

Our study adds to a growing number to have used a D_2O tracer to compare fluid delivery between carbohydrate-electrolyte beverages (Davis, Lamb, Burgess, & Bartoli, 1987; Jentjens et al., 2006; Jeukendrup et al., 2009; Murray et al., 1997). In addition to qualifying the combined effect of gastric emptying and intestinal absorption on unidirectional fluid absorption, the method has the major advantage of being relatively noninvasive. A disadvantage is that efflux (secretion) and reabsorption are unquantifiable. It is also impossible to determine the total quantity of ingested fluid that is absorbed using the D_2O-accumulation method because of uncertainty of the compartmental fate of the ingested water and changes in compartmental volumes that occur with exercise and solute flux. For example, with Gatorade, greater sodium absorption might have expanded both plasma volume and water absorption from the intestine without a corresponding representative increase in plasma D_2O enrichment.

With regard to limitation to interpretation, the current D_2O accumulation data indicate that the rate of unidirectional flux of ingested fluid from the water placebo was overall not substantially different from that of Gatorade (Figure 2). However, change in plasma volume was moderately less in placebo than with Gatorade, implicating less total water in the extracellular fluid compartment. Lambert et al. (1997) used a triple-lumen tube and reported twofold faster net water absorption in the duodenum with placebo (31 $ml \cdot cm^{-1} \cdot hr^{-1}$) than with an isotonic 6% sucrose-glucose-sodium solution (15 $ml \cdot cm^{-1} \cdot hr^{-1}$). However, the pattern was reversed in the early jejunal segment with absorption rates of 3.8 and 11.9 $ml \cdot cm^{-1} \cdot hr^{-1}$, respectively, leaving only a trend for higher total absorption with water (12.4 vs 10.4 $ml \cdot cm^{-1} \cdot hr^{-1}$). Gisolfi et al. (1998) reported higher net water influx in the duodenal segment with water placebo than with hypotonic (197 mOsmol/kg), isotonic (295 mOsmol/kg), and hypertonic (414 mOsmol/kg) 6% carbohydrate-electrolyte solutions during 90 min of exercise, which was reversed in the jejunal segment to leave an overall small increase (802 $ml \cdot 50\ cm^{-1} \cdot hr^{-1}$) in net fluid flux with water compared with the other solutions (633–674 $ml \cdot 50\ cm^{-1} \cdot hr^{-1}$). As in the current study, the decline in plasma volume was least with water placebo and the hypotonic drink but greatest with Gatorade (Gisolfi et al., 1998). Another pertinent point from our data set was that although overall D_2O enrichment was not clearly different between placebo and Gatorade, first-half

enrichment was possibly less with Gatorade (Table 1). Therefore, in the case of the comparison between placebo and Gatorade, extrapolation from the data set and cited intubation work suggest that fluid absorption may have been marginally higher with placebo than with Gatorade. Furthermore, the observation of higher serum osmolality (Figure 2) and sodium concentrations (Figure 3) suggests higher relative solute influx from the intestine with Gatorade (Na^+ concentration was twofold higher in Gatorade than in the other two sports drinks), which should have drawn in additional fluid and attenuated the decline in plasma volume; however, this appeared not to be the case and might otherwise be explained by higher net gut fluid retention relative to placebo, an argument that also applies to PowerAde. This suggestion is supported by the intubation data of Gisolfi et al. (1998) indicating that a higher rate of unidirectional fluid absorption with placebo is the most likely explanation for the difference relative to Gatorade and PowerAde in plasma volume.

In the current study, performance was evaluated with a test of endurance peak power, which has been shown to predict cycling time-trial performance (Hawley & Noakes, 1992) and also has reliability comparable to that of other endurance performance tests (Bonetti & Hopkins, 2010). Notwithstanding the amplification in outcome and error in a performance test after a preload (Hopkins, Schabort, & Hawley, 2001), the observed 3% mean increase with Mizone Rapid versus water could represent a worthwhile improvement in performance, given the body of literature reporting similar effects of carbohydrate solutions versus water placebos (Brouns & Kovacs, 1997; Coombes & Hamilton, 2000), but the lower and unclear improvement with Gatorade and PowerAde might inform a mechanism. Performance in an incremental test is a proxy of maximal cardiovascular-respiratory exercise capacity. Cardiac output and muscle blood flow are strong candidate mechanisms limiting maximal oxygen uptake (Saltin, Calbet, & Wagner, 2006), with factors such as dehydration capable of reducing blood and stroke volume, cardiac output, and peak power (Nybo, Jensen, Nielsen, & Gonzalez-Alonso, 2001). Therefore, greater circulating volume with the Mizone Rapid might have been sufficient to account for the possible small performance gain.

Although hypotonic carbohydrate-electrolyte sports drinks might offer benefits over more concentrated drinks in shorter duration performances, larger carbohydrate intakes may be more beneficial over longer durations. In endurance competitions (cycling events, Ironman 70.3, Ironman races) athletes ingest carbohydrate at 60–80 g/hr (B. Pfeiffer and A. Jeukendrup, unpublished). Furthermore, a large sample study with isotonic beverages found that 20-km time-trial performance after a 2-hr preload may be optimized with a carbohydrate intake of 60–80 g/hr (Smith et al., 2010). However, controlled and adequately powered performance studies comparing hypotonic with isotonic-hypertonic beverages across a range of carbohydrate doses and exercise durations have not been conducted. The relative contribution of solution tonicity and carbohydrate dose could be evaluated via construction of concentrated but hypotonic carbohydrate solutions to deliver 80 g/hr or more by way of partially hydrolyzed glucose polymers. Furthermore, the ideal composition also depends on climatologic and environmental conditions, individual fluid-loss rates, and tolerance of carbohydrate.

In conclusion, changes in the physiological outcomes measured in the current study are consistent with earlier and faster absorption of the hypotonic oral rehydration solution Mizone Rapid than with the other sports drinks. Furthermore, we present some evidence to support a role for carbohydrate concentration in fluid absorption, with the more concentrated but isotonic solution PowerAde apparently being absorbed more slowly than the less concentrated but hypertonic solution Gatorade. The current evidence suggests that a hypotonic sports drink provides minimally to moderately faster fluid absorption than more concentrated isotonic-hypertonic sports drinks, warranting further research into the practical implications of hypotonic sports drinks over more concentrated formulations.

Acknowledgments

We thank Jasmine Thomson for assistance with blood collection, John Leiper for background information that assisted with formulation of the study design, and the participants for their commitment and energy. Funding assistance and the experimental drinks were provided by Frucor Ltd., Auckland, New Zealand.

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