Hydration During Exercise in Warm, Humid Conditions: Effect of a Caffeinated Sports Drink


Caffeine is regarded as a diuretic despite evidence that hydration is not impaired with habitual ingestion. The purpose of this study was to determine whether a caffeinated sports drink impairs fluid delivery and hydration during exercise in warm, humid conditions (28.5 °C, 60% relative humidity). Sixteen cyclists completed 3 trials: placebo (P), carbohydrate-electrolyte (CE), and caffeinated (195 mg/L) sports drink (CAF+CE). Subjects cycled for 120 min at 60–75% VO\(_{2\text{max}}\) followed by 15 min of maximal-effort cycling. Heart rate and rectal temperature were similar until the final 15 min, when these responses and exercise intensity were higher with CAF+CE than with CE and P. Sweat rate, urine output, plasma-volume losses, serum electrolytes, and blood deuterium-oxide accumulation were not different. Serum osmolality was higher with CAF+CE vs. P but not CE. The authors conclude that CAF+CE appears as rapidly in blood as CE and maintains hydration and sustains cardiovascular and thermoregulatory function as well as CE during exercise in a warm, humid environment.

**Key Words:** carbohydrate, core temperature, fluid delivery, D\(_2\)O

During exercise in the heat, the loss of body fluid via sweating can result in dehydration, which might adversely affect thermoregulatory and cardiovascular function (5, 24, 36), as well as performance in prolonged exercise (2, 3, 8). Thus, during exercise in the heat, the provision of fluid to offset body-fluid losses from sweating is a priority for safety and maintaining exercise performance. Research over the past several decades indicates that moderately concentrated sports drinks containing 4–8% carbohydrate are appropriate for ingestion during prolonged exercise in the heat (11, 16, 33, 34). These solutions facilitate performance by simultaneously providing carbohydrate for energy and replacing fluid and electrolytes to maintain hydration (8, 37).

Millard-Stafford is with the School of Applied Physiology, Georgia Institute of Technology, Atlanta, GA 30332-0356. Cureton and Trilk are with the Dept of Kinesiology, University of Georgia, Athens, GA 30602-6554. Wingo is with the Institute for Exercise and Environmental Medicine, Presbyterian Hospital of Dallas, Dallas, TX 75231. Warren is with the Division of Physical Therapy, Georgia State University, Atlanta, GA 30302-4019. Buyckx is with The Beverage Institute for Health and Wellness, The Coca-Cola Company, Atlanta, GA 30313.
Whether additional legal and safe ingredients can augment the benefits of sports drinks during exercise in warm ambient conditions remains of interest (42). Caffeine might not be viewed as a viable additive because of its long-standing classification as a diuretic (26). Recent investigations, however, indicate that regular daily consumption of caffeine does not impair overall long-term hydration status (2, 6, 21, 24, 41), especially at relatively low doses (39). When caffeine is ingested in conjunction with exercise in thermoneutral environments, studies indicate that acute caffeine ingestion does not promote greater diuresis during or after exercise (29, 30, 44). After exercise in the heat, however, a caffeinated beverage impaired rehydration compared with both water and a sports drink (22). We are aware of only 1 study (45) that has examined the acute administration of a caffeinated sports drink during exercise in warm, humid conditions, and those authors reported no impact on urine production. Thus, additional information is needed to determine caffeine’s acute effect on hydration status during exercise when the environment is thermally challenging.

Several decades ago, it was observed that caffeine relaxes smooth muscle in the gastrointestinal tract (40), prompting assumptions that caffeine might hinder fluid replacement by delaying gastric emptying (23). The effect of caffeine on gastric emptying at rest is unclear (9) and is yet to be examined during high-intensity exercise. A recent study (46) in a thermoneutral environment indicated that caffeine added to liquid carbohydrate increased carbohydrate oxidation during exercise. The authors speculated that this was a result of enhanced intestinal absorption compared with liquid carbohydrate without caffeine.

Therefore, the purpose of the present study was to investigate 1) fluid delivery using a relative index that reflects both gastric emptying and intestinal absorption and 2) other hydration-related parameters of a caffeinated sports drink compared with a noncaffeinated sports drink. It was hypothesized that during strenuous exercise in warm, humid conditions (i.e., conditions during which net fluid delivery into the bloodstream might be challenged), a caffeinated sports drink would exhibit the same rate of fluid appearance in the blood and, therefore, be as effective in maintaining hydration and thermoregulation during prolonged exercise as a noncaffeinated, commercially available sports drink and placebo control.

**Methods**

**Subjects**

Sixteen healthy, highly trained male cyclists were recruited and studied at 2 institutions (10 at the University of Georgia and 6 at Georgia Institute of Technology). This sample size is sufficient to detect a moderate effect (0.6 SD) in hydration measures such as sweat rate, urine volume, and fluid retained using a 1-way ANOVA with repeated measured with an alpha level of 0.05 and power of 0.73, assuming a correlation between repeated trials of 0.7 (38). Subjects trained an average (±SD) of 264 ± 125 km/wk of cycling for 6 mo before the study. Mean (±SD) age, height, weight, percentage fat estimated from skinfolds, and maximal oxygen uptake (VO$_{2\text{max}}$) were 27.5 ± 7.0 y, 177.0 ± 5.9 cm, 72.7 ± 6.4 kg, 12.2% ± 4.6%, and 60.5 ± 7.2 mL·kg$^{-1}$·min$^{-1}$, respectively. All subjects habitually ingested caffeine, but daily intake varied from 9 to 482 mg, averaging 150 ± 113 mg. Subjects
signed an informed-consent statement approved by their respective institutional review boards and were paid for their participation.

Research Design

A double-blind, placebo-controlled, repeated-measures experimental design was used, in which all subjects were tested under all conditions. After a preliminary test session in which subjects had VO$_{2\text{max}}$ measured and were familiarized with test procedures, 3 experimental trials were completed in random order, separated by at least 5 d. During an experimental trial, 1 of 3 beverage treatments was administered before and during 2 h of cycling at a standardized intensity (60% and 75% VO$_{2\text{max}}$), followed immediately by a 15-min self-selected-pace ride at maximal effort. All trials took place in an environmental chamber at 28.5 °C, 60% relative humidity, with fan airflow ~2.5 m/s. After cycling, subjects recovered for 20 min in normal laboratory conditions (21 °C, 40% relative humidity).

Treatments

Three experimental beverages were used: 1) an artificially sweetened (aspartame), flavored water placebo control; 2) a commercially available 6% carbohydrate-electrolyte formulation (CE; Gatorade, Quaker Oats Co, Barrington, IL); and 3) a 7% commercially available carbohydrate-electrolyte beverage (Powerade, The Coca-Cola Company, Atlanta, GA) containing vitamins B$_3$, B$_6$, and B$_12$; 46 mg/L carnitine; 1.92 g/L taurine; and 195 mg/L caffeine (CAF+CE). Beverages administered on a given day were placed in uniform plastic containers identifiable to investigators and subjects only by numerical code. The fluid-ingestion schedule was patterned after recommendations of the American College of Sports Medicine to provide sufficient carbohydrate without compromising fluid availability (11). Subjects ingested half of a preexercise bolus of 6 mL/kg body weight 10 min before exercise and the other half immediately before exercise. During cycling, subjects ingested 3 mL/kg body weight (220 mL on average) of beverage at 15-min intervals. Total caffeine ingestion during the CAF+CE trial was 1.2 mg/kg before exercise, 3.5 mg/kg after 60 min, and 5.3 mg/kg for the entire protocol.

Protocol and Procedures

**Preliminary Test Session.** During the preliminary test session, body mass was measured to the nearest 10 g with an electronic scale (model FW-150KA1, A&D Co, Ltd, Tokyo), and skinfold thickness at 7 sites was measured using Lange calipers to estimate body fatness. A graded exercise test was conducted to measure VO$_{2\text{max}}$ on an electronically braked cycling ergometer (Lode Excalibur Sport, Lode BV, Groningen, The Netherlands). After a brief warm-up, power output was set at 200 W and progressively increased 25–50 W every 2 min until the point of volitional fatigue. Oxygen uptake (VO$_2$) and related gas-exchange measures were obtained by open-circuit spirometry with a PARVO Medics TrueOne 2400 metabolic measurement system (Parvo Medics, Inc, Salt Lake City, UT). Heart rate (HR) was measured every 2 min and at the end of the VO$_{2\text{max}}$ test with a Polar Vantage XL monitor (model 145900, Polar Electro, Inc, Woodbury, NY).
After a recovery of about 20 min, elements of the exercise used in the experimental protocol were practiced, and the metabolic intensities (%VO\textsubscript{2max}) at which each subject would be cycling were verified. The practice session concluded with 15 min of cycling in which subjects performed as much work as possible to become familiar with the maximal-effort performance.

**Experimental Controls.** For the experimental trials, participants were instructed to perform a similar training volume for the 3 d before and to avoid vigorous exercise the day before. In addition, they were instructed to maintain a standard mixed diet for 2 d before each trial. Food records were kept before the first trial, and meals were replicated by each subject for the remaining trials. Participants were instructed not to consume alcohol, caffeine, or nonprescription drugs the day before and on the day of a trial. Subjects reported in a normally hydrated condition, accomplished by drinking liberally the day before and drinking one 237-mL glass of water 1 h before the trial. Subjects refrained from exercise for 12 h before testing. They were tested at the same time of day for each trial, which was at least 3 h after a meal. On arrival at the laboratory, subjects completed a 24-h history form to assess compliance with pretest instructions and provided a urine sample. Urine specific gravity was measured with a refractometer, and hydration status was deemed acceptable if <1.021 (4).

**Experimental-Trial Protocol.** Before each trial, subjects measured their nude body weight and inserted a rectal temperature (T\textsubscript{re}) probe 10 cm past the anal sphincter. A Teflon catheter was then inserted into an antecubital vein. Subjects drank the first aliquot of the experimental test beverage and completed 100-mm visual analog scales to rate each beverage according to several aspects of taste and gastrointestinal (GI) tolerance.

After entering the environmental chamber, subjects sat upright on the cycle ergometer for 10 min to allow plasma volume to stabilize while resting T\textsubscript{re} and HR were measured and a 10-mL blood sample was drawn. They then ingested the second aliquot of beverage immediately before the start of the cycling test. This aliquot contained 0.15 g/kg body weight of deuterium oxide (D\textsubscript{2}O), which served as a qualitative marker of relative fluid uptake into the blood (17).

Subjects cycled for a total of 135 min. The first 120 min were performed at fixed intensities alternating between 60% and 75% VO\textsubscript{2max} every 15 min using the hyperbolic mode on the ergometer. For the last 15 min, subjects were told to ride as hard as possible (with the ergometer in linear mode), simulating an extended all-out effort at the end of a race. During the ride, T\textsubscript{re} and HR were measured every 5 min, and VO\textsubscript{2} was measured for the last 2 min of each 15-min interval.

After cycling, subjects exited the testing chamber into a cool laboratory to recover. They then dried off with towels before obtaining a nude, dry body weight. Urine production was measured, with subjects voiding into a collection container during cycling (when necessary on rare occasions) and after the postexercise body weight was obtained. Subjects then repeated the visual analog scales to evaluate beverage taste and GI tolerance.

**Body-Fluid Measures.** Ten-milliliter blood samples were obtained immediately before exercise and at 5, 10, 15, 20, 30, 60, 90, and 120 min into exercise, as well as immediately after the final 15-min performance ride. Hematocrit was measured
using a microhematocrit centrifuge, and hemoglobin concentration was measured using a HemoCue B-Hemoglobin photometer (HemoCue, Inc, Lake Forest, CA). Plasma-volume change during cycling relative to preexercise rest was calculated using the equations of Dill and Costill (18). Serum osmolality was measured by freeze-point depression with a Fiske (model 110) osmometer at one site \( (n = 10) \) and MicroOsmette (Precision Systems Inc) at the other site \( (n = 6) \). Although different instruments were used, changes over time were similar (no Beverage × Site interaction). The net change from baseline osmolality was also analyzed. Blood D\(_2\)O concentration was determined in purified plasma samples as described by Davis et al. (17) using an isotope ratio mass spectrometer (Center for Applied Isotope Studies, University of Georgia). Serum electrolytes were measured by reflectance spectrophotometry (Johnson & Johnson DTE) at the Georgia Institute of Technology and with a Roche Diagnostics 9180 electrolyte analyzer at the University of Georgia.

Sweat rate during the cycling test was estimated from net change in nude body weight and corrected for exhaled metabolic carbon and respiratory water (35), blood loss, any urine voided during exercise, and weight gained from fluid ingestion. Fluid retention was calculated as the difference between the fluid volume ingested and urine output.

**Statistical Analysis**

Data from the experimental trials were analyzed using a 3-way (Beverage × Time × Site) mixed-model analysis of variance (beverage and time as repeated measures and site as a between-subjects factor). There were no significant main effects for site or Beverage × Site interaction, indicating that results related to differences among beverages were the same at both test sites. Thus, data from the 2 sites were pooled and are presented as means with standard deviations (SD). Post hoc paired \( t \)-tests and simple-effects tests were performed to compare individual mean differences. The Bonferroni alpha-level correction was used to control the family-wise error rate to hold the experiment-wise alpha level at 0.05.

**Results**

**Hydration Measures**

Preexercise body mass, 72.4 ± 5.8, 72.3 ± 6.1, and 72.1 ± 6.2 kg, and urine specific gravity, 1.010 ± 0.006, 1.011 ± 0.007, and 1.011 ± 0.006, were not different under placebo, CAF+CE, and CE treatments, respectively. Serum osmolality was 286.4 ± 4.1, 288.0 ± 4.3, and 286.1 ± 4.0 mmol/kg for placebo, CAF+CE, and CE, respectively, before exercise. These measures indicate that subjects were euhydrated and in a similar initial state of hydration before the onset of the cycling protocols.

Postexercise body mass was also similar for placebo, CAF+CE, and CE (71.5 ± 6.1, 71.4 ± 6.2, and 71.2 ± 6.3 kg, respectively). As designed, total fluid intake during the 135 min of cycling was similar among treatments, averaging just over 2 L (Table 1). Relative dehydration (percentage change in body weight) and sweat rate were not different among beverages (Table 1). There also were no significant differences in fluid retention or urine output (Table 1) during cycling. Only a slight
tendency for greater diuresis (110 mL) and lower fluid retained from the ingested volume (4%) was observed for CAF+CE compared with CE and placebo.

The appearance of D₂O in blood within 30 min of ingestion is illustrated in Figure 1. D₂O concentrations during placebo, CE, and CAF+CE were not different (P > 0.05), indicating a similar time course of fluid delivery. Serum electrolyte levels were also not different among beverage trials (Figure 2). Serum sodium was well maintained under all treatments despite a variable beverage sodium content of 0, 10, and 20 mEq/L in placebo, CAF+CE, and CE, respectively. Serum osmolality is presented in Figure 3. There was a significant main effect for beverage. Values near the end of exercise (Minutes 120 and 135) were significantly higher (P < 0.05) for CAF+CE than for placebo but not different

<table>
<thead>
<tr>
<th>Variable</th>
<th>Placebo</th>
<th>CAF+CE</th>
<th>CE</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Δ Body weight</td>
<td>–1.4 ± 0.7</td>
<td>–1.3 ± 0.9</td>
<td>–1.3 ± 0.9</td>
</tr>
<tr>
<td>Total fluid intake (mL)</td>
<td>2132 ± 219</td>
<td>2100 ± 226</td>
<td>2128 ± 214</td>
</tr>
<tr>
<td>Sweat rate (mL/h)</td>
<td>1308 ± 181</td>
<td>1309 ± 262</td>
<td>1303 ± 220</td>
</tr>
<tr>
<td>Urine output (mL)</td>
<td>280 ± 230</td>
<td>390 ± 270</td>
<td>280 ± 180</td>
</tr>
<tr>
<td>Fluid retention (mL)</td>
<td>1835 ± 283</td>
<td>1769 ± 288</td>
<td>1847 ± 191</td>
</tr>
<tr>
<td>% Fluid retained during exercise</td>
<td>87.5 ± 11.1</td>
<td>83.2 ± 11.5</td>
<td>87.1 ± 7.6</td>
</tr>
</tbody>
</table>

No significant differences among beverage treatments were observed.
than CE. The net increase from baseline to postexercise osmolality was greater ($P < 0.05$) for CAF+CE (7.9 ± 7.3 mOsm/kg) and CE (6.7 ± 7.1 mOsm/kg) than for placebo (3.0 ± 8.8 mOsm/kg). Relative changes in plasma volume during cycling were not different among beverages or across time points (Figure 3).

**Physiological Measures**

Relative exercise intensity was standardized by alternating between 60% and 75% $\text{VO}_{2\text{max}}$ through 120 min and was maintained by all subjects. Average exercise intensity exerted over the final 15-min maximal-effort ride was significantly higher ($P < 0.05$) for CAF+CE (90.4% ± 11.2% $\text{VO}_{2\text{max}}$) than for CE (79.0% ± 14.1% $\text{VO}_{2\text{max}}$) and placebo (74.5% ± 11.7% $\text{VO}_{2\text{max}}$). Only during the sports-drink trials (CAF+CE and CE) could the subjects elevate their work rate above the previous standardized 75% $\text{VO}_{2\text{max}}$ intensity (i.e., the exercise intensity used immediately preceding the final 15-min ride).
There were no HR differences among beverages during the first 120 min, although HR oscillated between approximately 150 and 170 beats/min every 15 min (Figure 4A). During the final 15-min ride, when subjects freely chose their work output, HR was significantly higher ($P < 0.05$) with CAF+CE than with placebo or CE. The higher HR coincided with the greater exercise intensity exerted during this last portion of the CAF+CE trial. $T_r$ increased during exercise as expected (Figure 4B), with a significant Beverage $\times$ Time interaction. There were no significant differences among beverages through 60 min. Thereafter, $uP$ through Minute 120, $T_r$ for CAF+CE was slightly but significantly ($P < 0.05$) higher, by 0.19–0.29 °C, than with placebo. $T_r$ for CAF+CE was higher than for placebo from Minutes 120 to 135 and higher than for CE at Minutes 130 and 135, in parallel with the higher relative exercise intensity for CAF+CE.

### Beverage Palatability

There were no significant differences among beverages in the taste ratings for sweetness, sourness, or saltiness either before or after exercise. After exercise,
Hydration With Caffeinated Sport Drink

Figure 4 — Heart rate (Panel A) during cycling with 3 beverage treatments (mean ± SD). Rectal temperature (Panel B) during cycling with 3 beverage treatments (mean ± SD). P indicates placebo; CAF+CE, caffeinated sports drink; and CE, noncaffeinated sports drink. *CAF+CE vs. others, $P < 0.05$. †P vs. CAF+CE, $P < 0.05$. ‡CE vs. CAF+CE, $P < 0.05$.

beverage ratings for “thirst quenching” were significantly lower ($P < 0.05$) for placebo (39.5 ± 33.8) than for either sports drink (61.6 ± 27.6 and 61.2 ± 19.6). Postexercise ratings for desire to use the beverage during training were also lower for placebo (28.1 ± 30) than for CAF+CE (55.5 ± 33.5) and CE (56.9 ± 20.8). There were no differences among beverages in GI-tolerance ratings (e.g., stomach bloating, fullness, nausea), although these were all lower ($P < 0.05$) at baseline than after exercise.

Discussion

The purpose of this study was to investigate the acute effect of a caffeinated sports drink (CAF+CE) on fluid delivery and other hydration-related measures during cycling in warm, humid conditions compared with a traditional sports drink (CE) and placebo control. Gordon et al. (23) reported that caffeine (5 mg/kg) ingested before running in a warm environment had no effect on hydration-related variables in their study with a between-subjects design, but they used a small number of
runners (n = 5 in each group). Several studies have investigated whether caffeine added to a sports drink results in a diuretic effect during exercise (29, 30, 44), but only 1 was conducted in conditions in which fluid loss was exacerbated by a warm, humid environment (45). Our study extends the work of Wemple et al. (45) by determining whether caffeine added to a sports drink affects fluid absorption and other related fluid-balance measures using a relatively large sample of highly trained cyclists. Our primary findings were that caffeine added to a sports drink did not affect fluid delivery to the blood or elicit adverse fluid-balance or thermoregulatory effects during moderate- to high-intensity exercise compared with a noncaffeinated sports drink. Findings related to metabolic and peripheral or central fatigue effects underlying exercise performance have been discussed elsewhere (13).

Because there is no single measure that assesses all aspects of the hydrating effect of an ingested beverage (28), the effectiveness of the beverages in maintaining hydration was assessed using multiple methods. Fluid delivery into the blood, as reflected by the rate of change in blood D$_2$O concentration, was similar among the 3 beverages during exercise, consistent with studies on noncaffeinated sports drinks (15, 16, 33). These are the only data we are aware of comparing a qualitative marker of fluid appearance into the blood in caffeinated and noncaffeinated sports drinks. Recently, it has been theorized that caffeine added to carbohydrate enhances absorption more than liquid carbohydrate alone (46). Neither sports drink in our study, however, had a D$_2$O-appearance profile suggestive of greater fluid delivery into the blood than the other. The lack of differences observed in the relative index of fluid delivery for a sports drink compared with water during exercise is similar to 2 other exercise studies conducted in warm to hot conditions (31, 34) but different from a study at rest in cool conditions (17). Our observations also are consistent with the report (44) of no difference between caffeinated and noncaffeinated sports drinks in gastric emptying rate, oral–cecal transit time, and intestinal permeability during prolonged cycling in cool conditions. D$_2$O accumulation is a qualitative marker of fluid absorption and was measured relatively early (first 30 min) in the exercise bout in our study. Thus, it was important to use additional measures after exercise to assess fluid status. We observed no differences among the beverages in GI discomfort after prolonged exercise with any of the drinks, which is somewhat different than the observations from a study on running (44) that reported no greater GI distress with a caffeinated sports drink than with a noncaffeinated sports drink but more complaints with both sports drinks than with water.

The plasma-volume change during exercise was nearly identical for our 3 experimental drink conditions, decreasing about 9% during the first 30 min and remaining relatively constant thereafter. Therefore, blood volume, the most critical fluid compartment for performance of prolonged exercise, was not detrimentally affected by the caffeinated beverage. These data are not unlike those from other studies using a larger, single bolus of caffeine (without carbohydrate coingestion) during prolonged exercise in warm to hot conditions (10, 20, 23). It might be argued that plasma-volume change is not a sensitive marker of hydration status. Nonetheless, improved maintenance of plasma volume accompanied by reduced HR and thermoregulatory drift has been reported with 6% glucose-electrolyte drink compared with mineral water or carbohydrate drink without electrolytes during prolonged exercise in the heat (31). Likewise, fluid ingestion attenuates cardiovascular drift and maintains thermoregulation during cycling in the heat (25, 36).
The state of hydration throughout the experimental trials was also quantified by comparing body-weight stability, fluid retention, urine output, and serum electrolytes. None of these variables differed between the caffeinated- and noncaffeinated-sports-drink treatments. Net body-weight loss, occurring despite fluid ingestion, was the same for all beverages, averaging 0.9 kg, or slightly more than 1% of body weight. Most studies have shown that there is no acute effect of caffeine consumed either with (29, 45) or without carbohydrate (10, 19, 20, 21, 23) on body-weight change or sweat loss during prolonged exercise. Falk et al. (20), however, observed 12% higher sweat losses ($P = 0.07$) with 7.5 mg/kg of caffeine ingested within 2 h of a treadmill run to exhaustion at 70–75% VO$_{2\text{max}}$. We are aware of only 1 other study (22) that reported that caffeine impairs rehydration, but that was after exercise. Our values for fluid retention (83–87% of total fluid ingested) are on the high end of the range reported (24) in nonexercising, free-living subjects for both water and caffeinated beverages (e.g., coffee, soft drinks). Ingested fluid retained with CAF+CE was only 78 and 66 mL less than with CE and placebo, respectively. These differences are too small to be clinically meaningful. Moreover, our reported difference between CAF+CE and CE in urine output of ~0.11 L, a mere 0.17% of total-body water (63.5 L, based on an estimated 73% of the fat-free mass), is inconsequential for body functions. Serum sodium and potassium levels also were unaffected by ingestion of either sports drink compared with nonelectrolyte placebo. This is in contrast to 1 report (32) that caffeine attenuates the rise in [K$^+$] during exercise, prompting speculation by those authors that caffeine helps maintain the membrane potential in contracting muscle.

The lack of a significant acute diuretic effect for the caffeinated sports drink during exercise is in agreement with at least 2 other studies. During 1 h of cycling in cool conditions, urine output was low (ranging from 199 to 320 mL) and similar among water, sports drink, and sports drinks with 150, 225, and 320 mg/L of caffeine (30). In a study conducted in conditions similar to the present one (45), caffeinated (250 mg/L caffeine) and noncaffeinated sports drinks (Gatorade) were ingested during 1 h of rest followed by 3 h of cycling at 60% VO$_{2\text{max}}$ with a limited number of subjects ($n = 6$; 4 men, 2 women). Their caffeinated sports drink contained a slightly higher caffeine concentration (250 mg/L) and was ingested in a pattern similar to ours (3 mL/kg of beverage every 20 min) after 1 h of exercise. Because 8 mL/kg of the beverage containing 250 mg/L caffeine was ingested at 0 and 60 min of exercise, their total caffeine dose was higher (>8 mg/kg). Urine flow rate was significantly ($P < 0.01$) greater with their caffeinated beverage than with placebo at rest, but there was no difference during exercise. A lower urine flow rate during exercise was attributed to greater catecholamine release, which enhances electrolyte reabsorption and reduces glomerular filtration rate, with the overall net effect of less fluid being available for the kidney to eliminate during exercise.

Only a single measure related to hydration status was significantly different among beverage treatments. Serum osmolality was higher for CAF+CE than for placebo by the end of exercise but not significantly different than CE. In fact, both sports-drink trials resulted in over twice the elevation in osmolality from baseline (net increase of 7 and 8 mOsm/kg) compared with placebo (3 mOsm/kg) but were not accompanied by any other physiological changes reflecting reduced hydration status. Convertino et al. (12) found a similar absolute rise in blood osmolality during only 6 min of cycling at relatively high exercise intensity (70–90% VO$_{2\text{max}}$). This,
too, occurred without reflecting a meaningful change in hydration status. Although plasma hyperosmolality has been linked to the suppression of thermoregulatory responses (using a saline-infusion model), endurance-trained athletes acclimatized to the heat might not experience the same attenuation (27). Hyperosmolality could be related to the carbohydrate provided in the sports drink, which results in significantly higher blood concentrations of glucose. It is important to note that the caffeinated sports drink also provided scant amounts of carnitine (80 mg) and taurine (4 g over the entire trial). To our knowledge, the effects of these ingredients on hydration or serum osmolality have not been investigated, but compared with the 60–70 g of carbohydrate per liter of sport drinks (over 120 g total), they represent a minor contribution to the total energy density of the beverage. Our data indicate that increased osmolality of the magnitude observed caused no impairments in thermoregulatory or sweating responses.

Finally, consistent with similar hydration markers among caffeinated and noncaffeinated sports drinks, we also found no difference during the first 120 min of cycling for the cardiovascular and thermoregulatory variables. A caffeine dose (5–6 mg/kg) before exercise in warm conditions (28 °C) increased plasma epinephrine (1), which could explain increased HR, blood-pressure, and thermoregulatory responses to exercise (14, 43). Moreover, Daniels et al. (14) reported forearm blood flow attenuated by 53% with caffeine during cycling, which could impair heat dissipation. $T_r$ and HR, however, were unaffected during cycling at 65% VO$_{2\text{max}}$ in cool conditions (14) even with twice the caffeine dose of 10 mg/kg (19). Furthermore, another follow-up study by the same group reported no effect of caffeine on forearm blood flow in hot conditions (43). In addition, calculated heat storage was the same with caffeine despite higher oxygen uptake during a run to exhaustion in warm conditions (20). In a summer field study (10), no differences were observed in body temperature or blood parameters after a 21-km road race during which the athletes ingested 0, 5, or 9 mg/kg caffeine. In the present study, higher HR and $T_r$ with CAF+CE than with CE in the final 5 min of the performance ride would be expected because of the greater exercise intensity elicited with CAF+CE. Consistent with other published studies (7, 10, 23) conducted in warm-to-hot conditions, there were no acute adverse thermoregulatory effects with acute ingestion of a similar total caffeine dose, ~ 5 mg/kg.

Based on the results of this study, we conclude that the caffeinated sports drink investigated is absorbed as rapidly into the blood and maintains hydration, blood volume, and cardiovascular and thermoregulatory functions during prolonged exercise in warm, humid conditions as well as either a noncaffeinated commercially available sports drink or a flavored water control. Moreover, because fluid did not appear in the bloodstream sooner when drinking a moderately concentrated caffeinated sports drink (<200 mg/L) than with a noncaffeinated carbohydrate drink, intestinal absorption and gastric emptying rates are not altered by a caffeinated beverage during exercise.

**Acknowledgments**

This research was supported by a grant from The Coca-Cola Company, Atlanta, GA. We acknowledge the assistance of Matthew Ganio, Catherine Passariello, Lora Raines, Andrea Pinzon, Blythe Barrett, Beth Siwy, Richard Welling, Kristen Hitchcock, Teresa Snow, and Linda Rosskopf with collection of the data.
References


