Effects of Carbonated and Noncarbonated Beverages at Specific Intervals During Treadmill Running in the Heat

G. Patrick Lambert, Timothy L. Bleiler, Ray-Tai Chang, Alan K. Johnson, and Carl V. Gisolfi

Eight male runners performed four 2-hr treadmill runs at 65% $\dot{V}O_2$max in the heat (35°C, 15–20% RH). A different beverage was offered each trial and subjects drank ad libitum for 2 min every 20 min. The beverages were, 6% carbohydrate (CHO) solution (NC 6), 6% carbonated-CHO solution (C 6), 10% CHO solution (NC 10), and 10% carbonated-CHO solution (C 10). NC 6 and C 6 contained 4% sucrose and 2% glucose. NC 10 and C 10 contained high fructose corn syrup. Subjects drank more NC 6 than C 6. Fluid consumption was not different among other trials. During all trials, volume consumed and %ΔPV declined while heart rate and rectal temperature increased ($p<0.05$). No significant differences occurred between beverages for these variables. Percent body weight lost was greater ($p<0.05$) for the C 10 trial compared to the NC 6 trial. Neither sweat rate, percent fluid replaced, plasma $[Na^+]$, $[K^+]$, osmolality, percent of drink volume emptied from the stomach, or glucose concentration differed among trials. Plasma $[K^+]$ and osmolality increased ($p<0.05$) over time. Ratings of fullness and thirst were not different among beverages, although both perceptions increased ($p<0.05$) with time. It is concluded that (a) carbonation decreased the consumption of the 6% CHO beverage; (b) fluid homeostasis and thermoregulation were unaffected by the solutions ingested; and (c) fluid consumption decreased with time, while ratings of fullness and thirst increased.

Key Words: dehydration, drinking, gastric emptying, thirst

Prolonged exercise frequently results in dehydration characterized by plasma hyperosmolality, hypovolemia, cardiovascular drift, and hyperthermia (12, 25, 29, 34, 37). These disturbances are often attributed to inadequate fluid replacement (8), in part because the human thirst mechanism does not stimulate sufficient fluid ingestion to replace fluid losses sustained during exercise-heat stress (12). This phenomenon has been termed voluntary dehydration (1).

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Fluid ingestion during work in the heat is influenced by a number of factors including beverage palatability, sweetness, and temperature (15, 16). A proper combination of these variables may increase the consumption of fluids and result in improved fluid homeostasis, thermoregulation, and endurance performance (16). The optimal temperature for a fluid replacement solution is unclear, but cooler (6–22°C) solutions tend to be consumed in larger quantities during prolonged work in the heat (2). The perceived palatability of a fluid may vary from individual to individual, although flavoring the fluid and/or including a carbohydrate source as a sweetener seems important in improving this factor (15). The addition of sodium (20–30 mEq·L⁻¹) to a fluid replacement beverage has also been recommended as useful in promoting absorption, enhancing palatability, and replacing salt lost in sweat (13).

The rate at which an ingested fluid empties from the stomach is also important in maintaining body fluid balance during prolonged exercise. Drinking sufficient volumes at regular intervals during exercise is thought to maintain intragastric pressure and promote gastric emptying (GE) (9, 28, 32). Mitchell and Voss (24) demonstrated that consuming large fluid volumes (23 ml·kg⁻¹·h⁻¹) provided more rapid emptying from the stomach than moderate (17.1 ml·kg⁻¹·h⁻¹) or low (11.5 ml·kg⁻¹·h⁻¹) fluid volumes. Mitchell et al. (22) showed that beverages of lower carbohydrate content (e.g., 6%) empty from the stomach more rapidly than more concentrated solutions (e.g., ≥12%) during exercise. Furthermore, drink temperature may influence the rate of GE. Recent evidence suggests that warmer drinks may empty the stomach more rapidly than cooler solutions (20, 36), although this has not been a consistent finding and may be of little consequence (3, 9, 21).

The effect of beverage carbonation on fluid consumption and gastric emptying during exercise has not been examined thoroughly. At rest, Lolli and Smith (18) and Lolli et al. (17) found that GE can be increased by the presence of carbon dioxide in the stomach (produced by ingestion of an effervescent/sodium bicarbonate mixture or by ingesting carbonated water). In contrast, Zachwieja et al. (38) reported that adding carbonation to water did not influence GE compared to plain water when ingested immediately before a 15-min bout of cycle ergometry exercise. Furthermore, carbonation did not influence the feeling of fullness. Recent studies from this laboratory showed no effect of carbonation on GE or ad libitum fluid intake during prolonged treadmill running in the heat. However, sensations of GI distress were more prevalent when carbonated beverages were ingested during the ad libitum drinking study (33). A limitation to this study was that it was not applicable to race conditions, in which fluids are only available at specific times. Furthermore, most runners drink very rapidly when fluids are made available during a race, and some individuals do not tolerate rapid ingestion of carbonated beverages (unpublished observation).

With this in mind, the intent of the current investigation was to determine the effect of beverage carbonation on voluntary ingestion of fluids during treadmill running in the heat when the fluids were only available for a 2-min period every 20 min. It was hypothesized that the addition of carbonation to a fluid replacement beverage would reduce fluid consumption. Special attention was given to perceptions of beverage palatability, GI comfort, GE, and the resulting effects on fluid homeostasis and thermoregulation.
Methods

Eight male runners were recruited for this study. Their mean (±SE) age and maximal oxygen consumption (\(\dot{V}O_{2}\max\)) were 29.5 ± 3.0 yrs and 55.2 ± 4.1 ml·kg·min\(^{-1}\), respectively. Training distances ranged from approximately 40 to 100 km·wk\(^{-1}\). Informed consent was obtained from each subject prior to the start of the study, and all were cleared for participation after undergoing a physical examination. All subjects became acclimated to the heat by running approximately 1 hr·day\(^{-1}\) for a minimum of 1 week in the test environment (35°C at 15% relative humidity).

\(\dot{V}O_{2}\max\) was obtained via a progressive treadmill protocol, and the speed required to elicit 65% \(\dot{V}O_{2}\max\) (range 56–77% \(\dot{V}O_{2}\max\)) was determined. Prior to any experiments, each subject performed a practice trial to become familiar with the experimental protocol. Approximately 1 week following the practice run, each subject initiated a series of four 2-hr runs (separated by 2–14 days). All runs, including the practice trial, took place on a motor-driven treadmill in an environmental chamber maintained at 35°C dry bulb temperature and 15–20% relative humidity. To reduce variations in glycogen levels and hydration state between trials, each subject was reminded to maintain the same training routine between trials and to consume the same diet the day prior to and the day of an experiment.

Each trial is represented by the beverage supplied to the subject during that trial. Tap water was given during the practice trial, whereas one of the following beverages was provided during the actual experiments: (a) a 6% non-carbonated, carbohydrate solution (NC 6); (b) a 6% carbonated, carbohydrate solution (C 6); (c) a 10% noncarbonated, carbohydrate solution (NC 10); and (d) a 10% carbonated, carbohydrate solution (C 10). The characteristics of the beverages are found in Table 1. The order of experiments was balanced and the

| Table 1 |
|-------------------------|-------------------|-------------------|-------------------|-------------------|
| Characteristics of the Beverages Used in This Experiment Along With Other Commonly Consumed Beverages |

<table>
<thead>
<tr>
<th>Beverage</th>
<th>CHO* (%)</th>
<th>[Na(^+)] (mEq·l(^{-1}))</th>
<th>[K(^+)] (mEq·l(^{-1}))</th>
<th>Osmolality (mOsmol·kg(^{-1}))</th>
<th>Carbonation (vols·250 ml(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC 6</td>
<td>6</td>
<td>17.9</td>
<td>2.9</td>
<td>373.0</td>
<td>0.0</td>
</tr>
<tr>
<td>NC 10</td>
<td>10</td>
<td>11.3</td>
<td>3.6</td>
<td>621.5</td>
<td>0.0</td>
</tr>
<tr>
<td>C 6</td>
<td>6</td>
<td>23.8</td>
<td>2.7</td>
<td>355.0</td>
<td>2.3</td>
</tr>
<tr>
<td>C 10</td>
<td>10</td>
<td>3.15</td>
<td>4.1</td>
<td>608.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Coca-Cola</td>
<td>10.5</td>
<td>0.7</td>
<td>0.1</td>
<td>668.5</td>
<td>2.7</td>
</tr>
<tr>
<td>Pepsi-Cola</td>
<td>N/A</td>
<td>0.4</td>
<td>0.8</td>
<td>700.5</td>
<td>2.6</td>
</tr>
<tr>
<td>7 Up</td>
<td>N/A</td>
<td>2.85</td>
<td>0.0</td>
<td>654.5</td>
<td>2.6</td>
</tr>
</tbody>
</table>

*CHO composition: NC 6 = glucose & sucrose; NC 10 = high fructose corn syrup &/or sucrose; C 6 = glucose & sucrose; C 10 = high fructose corn syrup &/or sucrose; Coca-Cola = high fructose corn syrup &/or sucrose; 7 Up = high fructose corn syrup &/or sucrose.
subjects were blinded to the formulation of the drinks. Obviously, the carbonation
could not be disguised.

Upon entering the laboratory for an experiment, subjects donned their
running gear (shorts, socks, shoes), drank 400 ml of tap water, and completed a
pretrial questionnaire to assess their preexercise perception of thirst, mouth dry-
ness, fullness, and desire to drink different beverages. Responses were identified
by having the subject place a mark on a line of given length, with the extreme
left side corresponding to “not at all” or “very little” and the extreme right
corresponding to “very much.” These visual analog scales have been useful in
assessing thirst perception (31). To quantify the response, the mark was measured
as a percentage of the distance from the extreme left to extreme right of the line.
The subject then reclined on a cot and an 18-gauge catheter with a heparin lock
was positioned in a superficial forearm vein. Electrocardiograph (ECG) electrodes
were attached and their edges were coated with collodion to prevent them from
coming off during the experiment.

Upon entering the environmental chamber, each subject’s clothed and nude
weights were obtained (Acme scale, ±10 g) and the subject then stood on the
treadmill for 20 min to allow for plasma volume equilibration. At the end of 20
min, the subject was allowed to void and another clothed weight was obtained.
The difference between this weight and the initial clothed weight was subtracted
from the initial nude weight to yield the preexercise nude weight. The subject
then moved back to the treadmill where a blood sample (~10 ml) was obtained
in heparinized syringes for analysis. Subsequent blood samples were drawn every
30 min during the 2-hr run. Heart rate (by ECG) and T_{re} (via a clinical thermometer
inserted 6 cm) were obtained at Time 0 and at 15-min intervals thereafter.

Perception of thermal sensation (1–7 rating scale) and verbal assessment
of GI comfort, thirst, and salt appetite (verbal responses based on 1–4 or 1–5
rating scales, with 1 equal to “none” or “not at all” and 4 or 5 representing
“severe” or “very much so”) were obtained at Time 0 and every 20 min during
the trial. Ratings of perceived exertion also were recorded every 20 min (4).
Immediately following these questions, the subject stepped off the treadmill for
exactly 2 min and was allowed to drink the assigned beverage ad libitum. Drinking
occurred at 20, 40, 60, 80, and 100 min. The beverages were maintained at a
temperature of 10–15°C for all trials and were given to the subjects in unmarked
wide-mouth glass bottles.

Experiments were terminated early if T_{re} reached 40°C or if a subject
exhibited symptoms of syncope. Upon completing an experiment, subjects imme-
diately stepped off the treadmill and passed a nasogastric tube into the stomach
(French-Levine No. 12). Aspiration of gastric contents was accomplished with
a 60-ml syringe as the subject remained standing. Complete aspiration was
facilitated by instructing the subject to maneuver the tube within the stomach,
inserting or withdrawing it to various levels, and by bending the trunk and
contracting the abdominal musculature. The tube was then quickly removed and
a final nude weight was recorded after towel drying. The experiment was con-
cluded after the subject completed postexercise questionnaires to assess his overall
perception of the experimental beverage and his overall feelings of GI comfort
and thirst during and after the run. Responses to the questions were either given
by 1–4, 1–5, or 1–9 ratings or by visual analog responses as described above.

Blood samples were immediately analyzed in quadruplicate for hemoglobin
(cyanmethemoglobin method) and hematocrit (microcentrifugation) to determine percent changes in plasma volume (\%ΔPV) during the run (11). The remainder of the blood was centrifuged and the plasma was withdrawn and frozen for later analysis of glucose concentration (Sigma Kit no. 315), [Na⁺]/[K⁺] (Instrumentation Labs Model 943 flame photometer), and osmolality (Wescor Model 5500 Osmometer). Gastric residue samples were also analyzed for glucose concentration, [Na⁺]/[K⁺], and osmolality by the same procedures used for the plasma samples. GE was assessed as a percentage of the total fluid consumed. Thus the percent volume of drink emptied (%VOL$_{emp}$) was computed as follows:

\[
\text{%VOL}_{emp} = \frac{\text{VOL}_{tot} - \text{GR}_{vol}}{\text{VOL}_{tot}} \times 100
\]

where GR$_{vol}$ and VOL$_{tot}$ represent gastric residue aspirated following the run, and the total volume of drink consumed during the run, respectively. The volume of beverage consumed each 20 min was determined by subtracting the weight (g) of the bottles after drinking from the weight prior to drinking. The total volume consumed was taken as the sum of the volumes consumed from the five drinking periods. Sweat rate and percent body weight lost were calculated from the pre- to postweight difference, taking into account losses due to voiding, defecation, vomiting, blood collection, and gastric aspiration. Total volume consumed was expressed as ml·h$^{-1}$; volume consumed each 20 min was expressed as ml; sweat rate was expressed as L·hr$^{-1}$. Urine loss was determined by having the subject urinate into a plastic urinal at any time necessary during a trial. The volume was measured and expressed as ml. Percent fluid replaced was calculated as \% fluid replaced = total volume consumed / total fluid loss × 100, with weight losses due to blood collection, voiding, gastric aspiration, and vomiting excluded.

Carbonation content of the test beverages (Table 1) was analyzed using a Model D-T Piercing Device (Terriss-Consolidated Industries, Inc.). In determining this variable, 250 ml of each carbonated beverage, analyzed in triplicate, was slowly poured into a cold unmarked glass bottle and capped tightly (unmarked bottles were used to maintain the blind design). The bottle was then placed into the piercing device and pierced in a sealed fashion to allow for pressure measurements. The whole apparatus was subsequently shaken as a unit until no further increases in pressure were observed. Pressure and temperature were obtained from the device’s pressure gauge and thermometer, and carbonation content was read from a pressure-temperature chart. The chart expressed carbonation as the volumes of carbon dioxide gas pressure per volume of liquid.

Statistical analysis was performed using Pearson product moment correlation and either factorial, one-, or two-way ANOVA with repeated measures. The Fisher PLSD post hoc test was employed to identify significant differences with the level of significance set at \(p<0.05\). The data are expressed as mean ±standard error.

**Results**

Volume consumed was significantly greater for the NC 6 beverage compared to the C 6 beverage (994 ±177 to 585 ±108 ml·hr$^{-1}$, respectively) (Figure 1). There were no differences among other drink comparisons (\(p>0.05\)). Mean values were 743 ±90 and 640 ±74 ml·hr$^{-1}$ for NC 10 and C 10, respectively. Fluid ingestion was similar among the beverages at each drinking opportunity, but the volume
consumed significantly declined (p<0.05) with time, ranging from 384.15 ±39.91 ml at 20 min to 242.66 ±27.10 ml at 100 min (Figure 2). No significant differences were observed between trials for sweat rate (SR), percent fluid replaced (% fluid replaced), or urine loss (Table 2). Percent body weight lost (% BW lost) was significantly greater (p<0.05) for the C 10 trial compared to the NC 6 trial (1.65 ±0.14% to 1.13 ±0.23%, respectively) (Table 2). No differences were observed among other drink comparisons for this variable (p>0.05).

Exercise-heat stress resulted in significant changes (p<0.05) in HR, T_r, and %ΔPV during the experimental period, although no differences were found in these variables among beverages (Figure 3). HR increased significantly (approx. 80 bpm) (p<0.05) in the first 15 min of exercise and continued to rise at a lesser but significant rate (p<0.05) to the end. T_r also rose significantly (p<0.05) at the onset of exercise and continued to rise (p<0.05) over time. The %ΔPV significantly declined (p<0.05) during the run, except from 30–60 and 90–120 min, where nonsignificant declines occurred (Figure 3).

The experimental beverages differed not only in carbonation but also in osmolality, carbohydrate, and electrolyte content (Table 1). In spite of these differences, plasma values for [glucose], [Na⁺], [K⁺], and osmolality were not different between trials (p>0.05) (Figure 4). Values for [glucose], [K⁺], and osmolality increased significantly (p<0.05) with time, but no significant changes were found in [Na⁺] (p<0.09).

Table 3 shows the gastric emptying results. No differences were observed in percent volume emptied between trials. A significant correlation (r=0.79)
was observed between total volume of beverage consumed and percent volume emptied. Gastric residue osmolality was significantly lower for the NC 6 and C 6 beverages compared to NC 10 (p<0.05), possibly reflecting differences in preingestion osmolality of the drinks (Table 1). No other differences were observed among drinks for gastric residue osmolality, [Na⁺], [K⁺], or [glucose].
Figure 3 — Percent change in plasma volume, rectal temperature, and heart rate during the four trials. Values are mean ±SE.
Figure 4 — Plasma osmolality and plasma concentrations of sodium, potassium, and glucose during the four trials. Values are mean ±SE.
Table 3

Percent of Drink Volume Emptied and Gastric Residue Osmolality, Sodium, Potassium, and Glucose Concentrations

<table>
<thead>
<tr>
<th>Drink</th>
<th>Vol. emptied (%)</th>
<th>Osmolality (mOsm·kg⁻¹)</th>
<th>[Na⁺] (mEq·l⁻¹)</th>
<th>[K⁺] (mEq·l⁻¹)</th>
<th>[glucose] (mM)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SE</td>
<td>M</td>
<td>SE</td>
<td>M</td>
</tr>
<tr>
<td>NC 6</td>
<td>84.5</td>
<td>4.6</td>
<td>381.8</td>
<td>38.7*</td>
<td>34.7</td>
</tr>
<tr>
<td>C 6</td>
<td>73.9</td>
<td>5.8</td>
<td>328.5</td>
<td>25.1*</td>
<td>43.8</td>
</tr>
<tr>
<td>NC 10</td>
<td>76.6</td>
<td>6.8</td>
<td>492.3</td>
<td>29.2</td>
<td>33.3</td>
</tr>
<tr>
<td>C 10</td>
<td>74.7</td>
<td>6.9</td>
<td>415.4</td>
<td>36.2</td>
<td>34.9</td>
</tr>
</tbody>
</table>

*Significantly different from NC 10 (p<0.05).

Ratings of perceived exertion significantly increased over time (p<0.05) from 11.1 ±0.2, 11.5 ±0.2, and 11.6 ±0.4 at 20, 40, and 60 min, respectively, to 12.4 ±0.2, 12.5 ±0.2, and 13.1 ±0.3 at 80, 100, and 120 min, respectively. In addition, ratings of thermal sensation were significantly increased (p<0.05) at 20, 40, 60, 80, 100, and 120 min compared to 0 min, and at 120 min compared to 20 min, which coincided with the subjects’ inability to maintain thermoregulatory homeostasis.

Table 4 contains the pre- and posttrial questionnaire results. Significant increases (p<0.05) were observed in perceptions of thirst, mouth dryness, and desire to consume water and sport drinks. No differences were found pre- to postexercise for stomach fullness (posttrial responses were obtained following aspiration of the gastric contents) or desire to consume a carbonated drink. Results

Table 4

Pre- to Posttrial Perceptions of Thirst, Fullness, and Desire to Consume Various Beverages Based on Visual Analog Scale

<table>
<thead>
<tr>
<th>Question</th>
<th>Pretrial response</th>
<th>Posttrial response</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SE</td>
<td>M</td>
</tr>
<tr>
<td>Thirst</td>
<td>22.0</td>
<td>3.0</td>
<td>56.0</td>
</tr>
<tr>
<td>Like to drink now?</td>
<td>30.0</td>
<td>3.0</td>
<td>66.0</td>
</tr>
<tr>
<td>Mouth dryness</td>
<td>27.0</td>
<td>8.0</td>
<td>56.0</td>
</tr>
<tr>
<td>Stomach fullness</td>
<td>41.0</td>
<td>4.0</td>
<td>38.0</td>
</tr>
<tr>
<td>Like water now?</td>
<td>30.0</td>
<td>4.0</td>
<td>66.0</td>
</tr>
<tr>
<td>Like carbonated drink now?</td>
<td>23.0</td>
<td>4.0</td>
<td>31.0</td>
</tr>
<tr>
<td>Like sport drink now?</td>
<td>35.0</td>
<td>4.0</td>
<td>63.0</td>
</tr>
</tbody>
</table>

Note. Values are expressed on a 0-to-100 scale, 0 = “very little,” 100 = “very much.”
Posttrial responses obtained following gastric aspiration.
presented in Table 4 are the mean of all trials, as no differences were observed between beverages for these perceptions.

The results from responses obtained during trials concerning GI comfort, thirst, salt appetite, and desire to consume various beverages are found in Table 5. Significant increases ($p<0.05$) were observed over time in perceptions of thirst, stomach fullness, abdominal cramps, nausea, mouth dryness, desire to drink, and desire to drink water and sport drinks. Significant reductions ($p<0.05$) were noted over time in the desire for a carbonated drink and for something salty to eat. No differences were found between trials for these perceptions, thus the data are presented as means of all trials combined. It should be noted that while certain changes were found to be statistically significant, they may not represent physiological significance.

Significant differences ($p<0.05$) were observed for ratings of carbonation when carbonated beverages were compared to noncarbonated drinks, although no differences were found among beverages for other characteristics (sweetness, saltiness, or filling) (Table 6). Posttrial questionnaires (1–9 scale) revealed that the subjects would use the NC 6 (mean = 6.5 ±0.7) beverage during training and competition compared with the C 10 beverage (mean = 4.25 ±0.6) ($p<0.05$), but no other differences were observed between drinks for this preference. Mean values for the NC 10 and C 6 beverages were 4.6 ±0.8 and 4.7 ±0.9, respectively.

**Discussion**

The intent of this investigation was to determine whether adding carbonation to fluid replacement beverages (6% and 10% CHO) influences voluntary fluid consumption during prolonged running in the heat. Furthermore, we were interested in the effect that differences in consumption of carbonated versus noncarbonated drinks may have on GE, fluid balance, thermoregulation, and GI comfort. The results revealed a significant reduction in consumption of the carbonated 6% CHO beverage (C 6) compared to its noncarbonated control (NC 6), with a tendency for the carbonated beverages to be consumed less than the noncarbonated drinks (Figure 1). It is unclear why beverage C 6 was consumed less than beverage NC 6, while this was not statistically true between C 10 and NC 10. A possible explanation is that C 6 had a greater carbonation content (2.3 vols/250 ml) than C 10 (2.0 vols/250 ml).

The inability to match fluid loss with fluid consumption during prolonged work in the heat has been a concern for many years and was termed voluntary dehydration over four decades ago (1). This phenomenon was again exhibited in the present study. Sweat rates were approximately 1.7 kg·h⁻¹ in all trials with mean fluid intakes of only 0.73 kg·h⁻¹. This accounted for body weight losses of up to 1.65%, resulting in significant reductions in plasma volume and increases in HR and $T_{re}$ (Table 2 and Figure 3). There was a nonsignificant tendency for the C 6 beverage to defend plasma volume to a greater extent than the other drinks (Figure 3). Because we did not observe significant differences among trials in plasma osmolality, percent volume emptied, and percent fluid replaced, it is unclear why this trend appeared. A significantly greater reduction in percent body weight loss was observed in the C 10 trial compared to the NC 6 trial (Table 2). The reason for this is unclear but is most likely related to reduced but nonsignificant fluid replacement with this beverage (Table 2). It does not seem
Table 5
Perceptions of Thirst, GI Comfort, and Desire to Consume Various Fluids and/or Foods During 2-hr Run in the Heat Based on Verbal 1–4 Ratings

<table>
<thead>
<tr>
<th>Question</th>
<th>Time (min)</th>
<th>0</th>
<th>20</th>
<th>40</th>
<th>60</th>
<th>80</th>
<th>100</th>
<th>120</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>M</td>
<td>SE</td>
<td>M</td>
<td>SE</td>
<td>M</td>
<td>SE</td>
<td>M</td>
</tr>
<tr>
<td>Thirst</td>
<td></td>
<td>1.7</td>
<td>.09</td>
<td>2.4</td>
<td>.12a</td>
<td>2.2</td>
<td>.10a</td>
<td>2.3</td>
</tr>
<tr>
<td>Fullness</td>
<td></td>
<td>2.0</td>
<td>.11</td>
<td>1.9</td>
<td>.12</td>
<td>2.3</td>
<td>.13a,b</td>
<td>2.3</td>
</tr>
<tr>
<td>Abdominal cramps</td>
<td></td>
<td>1.0</td>
<td>.00</td>
<td>1.0</td>
<td>.03</td>
<td>1.0</td>
<td>.03</td>
<td>1.0</td>
</tr>
<tr>
<td>Sideache</td>
<td></td>
<td>1.0</td>
<td>.00</td>
<td>1.1</td>
<td>.06</td>
<td>1.0</td>
<td>.03</td>
<td>1.2</td>
</tr>
<tr>
<td>Heartburn</td>
<td></td>
<td>1.0</td>
<td>.00</td>
<td>1.0</td>
<td>.03</td>
<td>1.0</td>
<td>.00</td>
<td>1.1</td>
</tr>
<tr>
<td>Nausea</td>
<td></td>
<td>1.0</td>
<td>.00</td>
<td>1.0</td>
<td>.00</td>
<td>1.1</td>
<td>.08</td>
<td>1.1</td>
</tr>
<tr>
<td>Urge to defecate</td>
<td></td>
<td>1.0</td>
<td>.03</td>
<td>1.1</td>
<td>.05</td>
<td>1.4</td>
<td>.34</td>
<td>1.1</td>
</tr>
<tr>
<td>How pleasant to drink now?</td>
<td></td>
<td>2.0</td>
<td>.08</td>
<td>2.4</td>
<td>.12a</td>
<td>2.3</td>
<td>.10a</td>
<td>2.4</td>
</tr>
<tr>
<td>How much like water now?</td>
<td></td>
<td>1.9</td>
<td>.11</td>
<td>2.4</td>
<td>.13a</td>
<td>2.3</td>
<td>.12a</td>
<td>2.5</td>
</tr>
<tr>
<td>How much like carbonated drink now?</td>
<td></td>
<td>1.6</td>
<td>.12</td>
<td>1.4</td>
<td>.11</td>
<td>1.3</td>
<td>.11a</td>
<td>1.4</td>
</tr>
<tr>
<td>How much like sport drink now?</td>
<td></td>
<td>1.9</td>
<td>.11</td>
<td>2.3</td>
<td>.12a</td>
<td>2.3</td>
<td>.11a</td>
<td>2.4</td>
</tr>
<tr>
<td>How much like something salty now?</td>
<td></td>
<td>1.2</td>
<td>.07</td>
<td>1.2</td>
<td>.07</td>
<td>1.2</td>
<td>.07</td>
<td>1.2</td>
</tr>
<tr>
<td>How dry is mouth now?</td>
<td></td>
<td>1.7</td>
<td>.11</td>
<td>2.3</td>
<td>.08a</td>
<td>2.2</td>
<td>.07a</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Significantly different from: aTime 0; bTime 20; cTime 40; dTime 60; eTime 100.
Table 6

Posttrial Assessments of Beverages Based on Visual Analog Scale

<table>
<thead>
<tr>
<th>Question</th>
<th>NC 6 M</th>
<th>NC 6 SE</th>
<th>NC 10 M</th>
<th>NC 10 SE</th>
<th>C 6 M</th>
<th>C 6 SE</th>
<th>C 10 M</th>
<th>C 10 SE</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweetness</td>
<td>48.0</td>
<td>7.7</td>
<td>60.3</td>
<td>11.5</td>
<td>53.0</td>
<td>5.3</td>
<td>64.9</td>
<td>8.2</td>
<td>0.49</td>
</tr>
<tr>
<td>Carbonation</td>
<td>31.0</td>
<td>8.1</td>
<td>14.3</td>
<td>7.6</td>
<td>59.1</td>
<td>10.0†</td>
<td>77.4</td>
<td>4.2†</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Saltiness</td>
<td>33.1</td>
<td>8.7</td>
<td>38.4</td>
<td>8.2</td>
<td>48.5</td>
<td>10.3</td>
<td>45.3</td>
<td>7.0</td>
<td>0.60</td>
</tr>
<tr>
<td>Filling</td>
<td>54.0</td>
<td>6.5</td>
<td>59.4</td>
<td>5.1</td>
<td>62.8</td>
<td>6.2</td>
<td>70.4</td>
<td>9.3</td>
<td>0.44</td>
</tr>
</tbody>
</table>

Note. Values expressed as percentages of visual analog line, 0 = "very little" to 100 = "very much."

*Significantly different from NC 6; †significantly different from NC 10.

to be the result of greater sweat rates or urine losses, as these were not significantly different among the drinks (Table 2).

In the present investigation, neither CHO content (6 and 10%) nor carbonation in the drinks influenced gastric emptying (percent volume emptied), but we did not account for gastric secretion. The NC 10 and C 10 trials likely produced a greater gastric secretion due to their greater carbohydrate content. This would increase total gastric volume and, theoretically, could enhance GE (24). On the other hand, solutions with higher CHO content have been shown to empty more slowly from the stomach (22). Based on the change in residue osmolality of the NC 10 and C 10 solutions, from the original drink to the gastric residue value, considerable gastric secretion could have occurred. Thus the GE results for these drinks may have been underestimated. Furthermore, by not accounting for gastric secretion, percent volume emptied for all trials (mean = 77.4%) may have been underestimated.

Our result was somewhat lower than that found by Costill et al. (8), Mitchell et al. (23), and Ryan et al. (32), who showed at least 90% emptying of ingested fluids during prolonged exercise. Differences among the studies in the beverages consumed, mode of exercise, and exercise intensity most likely do not explain this disparity (8, 14, 27). Greater exercise-heat stress in the current study may have inhibited GE. Neufer et al. (26) showed that exercise-heat stress and hypohydration can significantly impair GE. Emptying of 400 ml of water was shown to be impaired while walking (50% VO₂ max) in a warm environment (35°C) in acclimated, hypohydrated individuals. Furthermore, there was a strong correlation (−0.76) between final exercise Tₑ and the amount of fluid emptied from the stomach. In the present study, Tₑ was above 39.0°C during the 2nd hour of exercise, which, according to Neufer et al. (26), could have reduced GE.

It is likely that the carbon dioxide of carbonated drinks is released from solution upon ingestion. This could theoretically affect both intragastric pressure and pH. While increased pressure may enhance GE, lowering the pH could inhibit it (7). Results from the present study suggest that carbonation does not
significantly affect GE during prolonged treadmill exercise in the heat (Table 3). These data agree with those of Zachwieja et al. (38), who found no difference in GE during 15 min of cycling after ingesting 5.5 ml·kg⁻¹ of either water, carbonated water, a carbonated 2-calorie sport drink, or its noncarbonated control. Our data also support earlier findings from this laboratory in which no differences were observed in GE between carbonated and noncarbonated solutions ingested at 0 (400 ml), 15, 30, and 45 min (200 ml) of treadmill running in the heat (1 hr) (33). This suggests that GE of water or fluid replacement beverages is not affected by carbonation. In contrast, Lolli and Smith (18) and Lolli et al. (17) reported enhanced GE at rest with ingestion of an effervescent/sodium bicarbonate mixture or carbonated water. The reason for the discrepancy between these early findings and more recent findings is unclear.

In the ad libitum drinking study by Ryan et al. (33), it was reported that subjective sensations of GI comfort and frequency of GI discomfort were greater with ingestion of carbonated beverages compared to noncarbonated controls. In contrast, Zachwieja et al. (38) found no differences in stomach fullness between carbonated and noncarbonated drinks. We also found no significant effects of carbonation on GI comfort in the present investigation. The reason for the discrepancy in GI comfort results is not clear, although the effect of volume ingested and/or the exercise mode may account for the differences between the study by Ryan et al. (33) (1.3 kg over 2 hrs of running) and Zachwieja et al. (38) (5.5 ml·kg⁻¹ in one feeding prior to 15 min cycling).

Mitchell and Voss (24) reported increased perceptions of stomach fullness during their high volume trials compared to both the medium and low volume trials. There was also a significant correlation (0.75) between the final fullness rating and the volume of drink remaining in the stomach at the end of exercise. Brouns et al. (6) reported increased incidence of GI complaints with running compared to nonjarring activities (e.g., cycling, cross-country skiing). The differences in GI comfort between the study by Ryan et al. (33) and the present investigation could be due to a greater degree of dehydration experienced by the subjects in their study (range 2.3–2.9%) compared to this study (range 1.1 to 1.6%). As previously discussed, hypohydration can affect GE and thus could affect GI comfort. On the other hand, mean consumption rate (0.65 and 0.74 kg·h⁻¹, respectively), exercise mode (TM running), and exercise-thermal stress (60% VO₂max / 32°C / 30% RH and 65% VO₂max / 35°C / 15–20% RH, respectively) were similar between the investigations.

Volume consumed for all trials decreased over the experimental period (Figure 2). Factors that may have contributed to this finding include stomach fullness and an increase in the stressfulness of the trial over time. We did not measure VO₂ during each trial, but perceived exertion increased significantly over time (11.1 at 20 min to 13.1 at 120 min). It is uncertain whether the changes observed in stomach fullness in this study demonstrate physiological significance (range 1.9 to 2.5 on a 1-to-4 rating scale). Rolls et al. (31) found that 24 hrs of water deprivation produced significantly heightened sensations of thirst in humans which were inhibited to predeprivation levels within 2.5–5 min of ad libitum drinking. These reductions in thirst precluded any major plasma osmolality changes. Maddison et al. (19) found that in water-deprived monkeys allowed to satiate themselves with heavy water intake, drinking could be induced by emptying the stomach via a gastric cannula.
It is therefore concluded that sensations of stomach fullness and gastric distension (fullness) reduce sensations of thirst. Interestingly, in the present investigation the sensation of thirst rose significantly with time in spite of the increased ratings of fullness. Other well-known factors that stimulate thirst are plasma hyperosmolality and angiotensin II (ANG II) (30). The exercise-heat stress imposed in this study significantly increased plasma osmolality levels and, presumably, plasma ANG II levels (5, 10, 35). It is possible that the inhibitory effect that gastric distension has on thirst may have been overridden by these factors. The reason why fluid consumption declined with increasing thirst is not clear. One explanation is that increased feelings of fullness may compete with the heightened urge to drink.

In summary, addition of carbonation to fluid replacement beverages does not significantly affect GE, thermoregulation, or fluid homeostasis during prolonged treadmill running in the heat under simulated race conditions. These responses occurred despite significantly reduced consumption of the C 6 beverage compared to the NC 6 beverage and a tendency for the carbonated drinks to be consumed in smaller amounts than the noncarbonated drinks. During prolonged treadmill running in the heat, ad libitum drinking under race-like conditions results in increased stomach fullness. Furthermore, volume consumption declines over time under the conditions imposed in this study. The reasons for these disturbances are unclear but may contribute to the voluntary dehydration commonly found during prolonged work in the heat.

References

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