Evaluating the effects of caffeine and sodium bicarbonate, ingested individually or in combination, and a taste-matched placebo on high-intensity cycling capacity in healthy males

Matthew F. Higgins, Susie Wilson, Cameron Hill, Mike J. Price, Mike Duncan, and Jason Tallis

Abstract: This study evaluated the effects of ingesting sodium bicarbonate (NaHCO₃) or caffeine individually or in combination on high-intensity cycling capacity. In a counterbalanced, crossover design, 13 healthy, noncycling trained males (age: 21 ± 3 years, height: 178 ± 6 cm, body mass: 76 ± 12 kg, peak power output (Wpeak): 230 ± 34 W, peak oxygen uptake: 46 ± 8 mL·kg⁻¹·min⁻¹) performed a graded incremental exercise test, 2 familiarisation trials, and 4 experimental trials. Trials consisted of cycling to volitional exhaustion at 100% Wpeak (Tlim) 60 min after ingesting a solution containing either (i) 0.3 g·kg⁻¹ body mass sodium bicarbonate (BIC), (ii) 5 mg·kg⁻¹ body mass caffeine plus 0.1 g·kg⁻¹ body mass sodium chloride (CAF), (iii) 0.3 g·kg⁻¹ body mass sodium bicarbonate plus 5 mg·kg⁻¹ body mass bicarbonate (BIC-CAF), or (iv) 0.1 g·kg⁻¹ body mass sodium chloride (PLA). Experimental solutions were administered double-blind. Pre-exercise, at the end of exercise, and 5 min post-exercise blood pH, base excess, and bicarbonate ion concentration ([HCO₃⁻]) were significantly elevated for BIC and BIC-CAF compared with CAF and PLA. TLIM (median; interquartile range) was significantly greater for CAF (399; 350–415 s; P = 0.039; r = 0.6) and BIC-CAF (367; 333–402 s; P = 0.028; r = 0.6) compared with BIC (313; 284–448 s) although not compared with PLA (358; 290–433 s; P = 0.249, r = 0.3 and P = 0.099 and r = 0.5, respectively). There were no differences between PLA and BIC (P = 0.196; r = 0.4) or between CAF and BIC-CAF (P = 0.753; r = 0.1). Relatively large inter- and intra-individual variation was observed when comparing treatments and therefore an individual approach to supplementation appears warranted.

Key words: caffeine, sodium bicarbonate, alkalosis, metabolic buffers, cycling.

Introduction

The individual ergogenicity of both caffeine (CAF) and sodium bicarbonate (NaHCO₃; BIC) has been extensively evaluated in vivo (Higgins et al. 2013a; Meyers and Cafarelli 2005; Simmonds et al. 2010) and in vitro (Higgins et al. 2013b; Tallis et al. 2012, 2013). Although not uniformly equivocal, recent evidence suggests that individually both CAF (Simmonds et al. 2010) and BIC (Higgins et al. 2013a) can exert ergogenic benefits on high-intensity exercise capacity (+15% at 120% peak oxygen uptake (VO₂peak)) and +17% at 100% peak power output (Wpeak), respectively. With CAF and BIC eliciting performance-enhancing effects by different mechanisms, a synergistic effect may occur resulting in substantial performance gains. However, to the best of our knowledge only 4 studies have evaluated the effects of combining CAF and BIC on exercise performance in vivo (Carr et al. 2011; Christensen et al. 2014; Kilding et al. 2012; Pruscinio et al. 2008). Carr et al. (2011) reported that compared with placebo, 6 mg·kg⁻¹ body mass CAF improved power output (PO) in elite cyclists by 11% when ingested in combination with 3 g·kg⁻¹ body mass BIC; however, BIC alone elicited a +9% effect. Hence, the potential for a taste-matched placebo on high-intensity cycling capacity in healthy males.
males during 2000-m rowing by 2.3%. This increase in PO contributed to a 3-s quicker completion time and in the context of the magnitude-based inference statistical approach adopted by the authors, was reported as very close to a substantial difference. In contrast, Carr et al. (2011) reported that the differences in PO and completion time between BIC and placebo (0.6%, 0.6 s) and combined BIC and CAF and placebo (1.7%, –1.2 s) were unclear. More simply, ingestion of BIC did not appear to augment 2000-m rowing performance compared with placebo. Interestingly, the ingestion of CAF with BIC resulted in a greater PO (1.1%) and faster completion time (~1.8 s) compared with BIC alone, suggesting that CAF ingestion somewhat ameliorated the performance decrement reported after isolated BIC ingestion, compared with placebo. However, it should be pointed out that all participants reported gastrointestinal (GI) issues, including nausea, vomiting, and stomach pain after BIC ingestion, regardless if coingested with CAF. When considering the between treatment coefficient of variation for mean performance time was 0.4%, it is plausible that these GI issues might have modulated the potential ergogenicity of BIC.

Pruscino et al. (2008) reported that CAF alone negatively impacted repeated 200-m freestyle swimming performance compared with all treatments (range: −1.5% to −0.9%). Performance was significantly slower with CAF compared with BIC (−1.5% ± 0.7%) and BIC and CAF combined (−1.2% ± 1.0%). In contrast, performance with BIC was quicker compared with all treatments (range: 0.3% to 0.7%), regardless whether ingested in isolation or with CAF. Indeed, the largest reported performance improvement, albeit small, was for BIC alone versus placebo (0.7% ± 0.7% faster). However, it should be pointed out that the sample size for this study was relatively small (n = 6) so results should be interpreted with caution. More recently, Kilding et al. (2012) reported that in comparison with placebo, both CAF and BIC significantly enhanced mean power output during 3-km time-trial performance in trained male cyclists (2.1% and 2.7%, respectively) although the ergogenic effects were not additive (2.4%). Based on the evidence to date the combinatorial effects of BIC and CAF on physical performance are therefore equivocal.

In addition to the aforementioned GI distress it seems plausible that differences in experimental approach between studies might have contributed to the differences in results previously reported. For example, although each study adopted a dosage of 3.5 g kg−1 BIC the dosage of CAF varied between studies, with Pruscino et al. (2008) and Carr et al. (2011) adopting −6 mg kg−1 whereas Kilding et al. (2012) and Christensen et al. (2014) adopted 3 mg kg−1. Additionally, there were differences in approaches to abstinence of CAF intake prior to exercise, an area recognised to limit the ability to compare studies evaluating the ergogenic effects of CAF (Tallis et al. 2015). For example, participants in Carr et al. (2011) and Pruscino et al. (2008) abstained for 48 h prior to exercise whereas participants in Kilding et al. (2012) abstained for the duration of the study. Participants in Christensen et al. (2014) were asked to avoid CAF drinks 36 h prior to testing. Furthermore, differences in exercise modality and protocol (e.g., repeated 200-m freestyle swimming (Pruscino et al. 2008), 2000-m rowing (Carr et al. 2011), 3-km time trial cycling (Kilding et al. 2012), and 6-min maximal rowing (Christensen et al. 2014)) might have contributed to differences between studies.

Each of the previous studies that have examined combined CAF and BIC ingestion on exercise performance evaluated well-trained participants, which might also have contributed to why no clear synergistic ergogenic benefit has been observed. Indeed it is now well established that individuals who undertake high-intensity training have elevated levels of muscle carnitine compared with endurance-trained and untrained individuals (Parkhouse and McKenzie 1984; Parkhouse et al. 1985). Carnitine, an intracellular buffer, is thought to play an important role in the homeostasis of muscle cells during high-intensity exercise (Derave et al. 2010) and thus might “offset” any potential ergogenic contribution from BIC (Aschenbach et al. 2000; Derave et al. 2010). A recent meta-analysis demonstrated that the overall mean effect of BIC on exercise performance was more than 225% greater in untrained (effect size: 95% confidence interval (CI): 0.59; 0.36–0.95) compared with trained (0.18; 0.13–0.33) individuals (Peart et al. 2012). The difference between untrained (0.69; −0.07 to 1.63) and trained (0.19; −0.58 to 1.07) individuals was particularly large (263%) for research using a time to volitional fatigue (Tlim) protocol (i.e., exercise capacity). This is supported by Matson and Tran (1993) who suggest that using Tlim is most likely to demonstrate ergogenic benefit for BIC supplementation. Indeed, recent research has demonstrated that ergogenic benefit with BIC ingestion is most likely observed for Tlim at 100% Wpeak (Higgins et al. 2013a). Similarly, Simmonds et al. (2010) demonstrated that 5 mg·kg−1 CAF increased Tlim at 120% Wpeak by −15%, although the ergogenic effects of CAF are generally more pronounced in trained compared with untrained individuals (Simmonds et al. 2010; Tallis et al. 2015).

Because of the small number of studies and myriad of differences between experimental approaches, the potential synergistic benefit of BIC and CAF outside the trained population is not currently known. This is important as there is evidence that increasing numbers of recreational athletes, the vast majority are both using and/or want to understand the safety and presumably efficacy of performance enhancing substances (Bojsen-Moller and Christiansen 2010). Moreover, both BIC and CAF are now widely available and marketed to recreational athletes. The present study, therefore, sought to address this gap in the literature by examining the effects of BIC and CAF, ingested individually and simultaneously, on Tlim in healthy but not specifically cycling-trained males. We hypothesised that ingesting BIC and CAF individually would enhance Tlim versus placebo. Additionally, we hypothesised that ingesting BIC and CAF simultaneously would enhance Tlim versus all experimental conditions.

Materials and methods

Participants

Thirteen healthy, noncycling trained males (age: 21 ± 3 years, height: 178 ± 6 cm, body mass: 76 ± 12 kg, Wpeak: 230 ± 34 W, VO2peak: 46 ± 8 mL·kg−1·min−1) volunteered for this study, which had received Coventry University Ethics Committee approval. All participants were recreationally active (engaging in physical activity at least twice weekly and were primarily team-sport athletes or middle-distance runners; International Physical Activity Questionnaire score: 5679 ± 6688 MET-min·week−1) although not specifically cycling-trained. Participants that completed the study habitually consumed CAF but were not heavy CAF users (125 ± 95 mg·day−1). CAF intake was measured using a 24-h recall questionnaire (Maughan 1999).

Pre-experimental procedures

Participants were screened to ensure that they were not currently undertaking or had undertaken a nutritional regime involving any alkalotic buffers such as BIC, sodium citrate, or β-alanine within the previous 3–6 months. Because of the high-intensity nature of the exercise trials participants were reminded to consume a balanced body mass-maintaining diet (−50% carbohydrate, −30% protein, and −20% fat) throughout the study. All

of this nutritional information was included in the participant information sheet provided and confirmed verbally before participants gave written informed consent. Each participant also completed a general health screening questionnaire before each trial. Participants visited the laboratory on 7 occasions and reported for each trial 2 to 3 h postprandial. Trials were conducted at the same time of day to avoid possible circadian rhythmic effects on exercise performance (Cappaert 1999).

**Study design**

On the first visit participants completed a graded incremental exercise test to determine $V_{\text{O2peak}}$ and $W_{\text{peak}}$. After at least 48 h rest participants undertook the first of their 2 familiarisation trials at a constant load equivalent to 100% $W_{\text{peak}}$ (Higgins et al. 2014). On the subsequent 4 visits, each separated by at least 48 h, participants completed $T_{\text{LIM}}$ at 100% $W_{\text{peak}}$ 60 min after consuming solutions containing either (i) 0.3 g kg$^{-1}$ body mass NaHCO$_3$ (BIC); (ii) 5 mg kg$^{-1}$ body mass caffeine plus 0.1 g kg$^{-1}$ body mass sodium chloride (CAF); (iii) 0.3 g kg$^{-1}$ body mass NaHCO$_3$ plus 5 mg kg$^{-1}$ body mass caffeine (BIC-CAF); or (iv) 0.1 g kg$^{-1}$ body mass sodium chloride (PLA). Both 0.3 g kg$^{-1}$ BIC (Higgins et al. 2013a) and 5 mg kg$^{-1}$ CAF (Simmonds et al. 2010) have been demonstrated to augment high-intensity cycling capacity. Experimental solutions were administered double-blind. In addition to the relevant solute, each solution consisted of 4 mL kg$^{-1}$ tap water and 1 mL kg$^{-1}$ of double-strength no added sugar orange squash (Sainsbury’s, London, UK). A dosage of 0.1 g kg$^{-1}$ body mass of sodium chloride (NaCl) was added to CAF and PLA drinks to taste-match the BIC-containing solutions as closely as possible. All solutions were refrigerated overnight before consumption to enhance palatability (Higgins et al. 2013a).

**Graded incremental exercise test**

Before commencing the graded incremental exercise test, participants selected the seat and pedal strap positions that felt most comfortable, ensuring that the leg was slightly flexed when the foot reached the bottom of each duty cycle. These settings were adopted for all subsequent trials. Participants were then seated and linked to a gas analysis system and rested quietly for 5 min. Expired gas was analysed using an online breath-by-breath system (Metamax 3B, Cortex Biophysik, Leipzig, Germany). Before each test the system was calibrated for gas concentration (5% CO$_2$ and 15% O$_2$, British Oxygen Company, Sutton, UK) using a 6-L antistatic rebreathable bag (Harvard Apparatus Ltd, Kent, UK), volume measured using a 3-L calibration syringe (Hans Rudolph Inc., Kansas, USA), and atmospheric pressure measured from a wall-mounted mercury barometer (F. Dalton & Co. Ltd., Watford, UK). Baseline data was averaged over the last 60 s of the rest period and for the last 10 s of exercise. Expired gas was continually monitored and values for $V_{\text{E}}$, $V_{\text{O2}}$, and RER were subsequently calculated. Heart rate (HR) was measured using a telemetric HR monitor (Polar FSI, Kempele, Finland). Participants were blinded to the clock during rest to minimise any anticipatory changes in baseline physiology. Prior to commencing exercise resting blood lactate concentration was obtained by means of a finger-prick capillary sample. The finger was wiped with an isopropyl alcohol swab (Medlock Medical, Oldham, UK), punctured using a 1.8-mm lancing device (Safety Lancet, Sarstedt, Germany) and the initial blood wiped away with a tissue. A 20-$\mu$L sample was collected in a sodium heparinised capillary tube (EKF Diagnostic, Magdeburg, Germany) and then added to a 2-mL Eppendorf tube, which was pre-filled with 1 mL of haemolysing solution (EKF Diagnostic) and mixed well. Samples were then analysed for blood lactate concentration (Biosen C Line, EKF Diagnostic).

Cycling commenced on the ergometer (Monark 824E Ergomedic, Monark, Varberg, Sweden) at a cadence of 70 r min$^{-1}$ with an unloaded cradle (70 W) increasing by 35 W every 3 min until volitional exhaustion. Researchers provided verbal feedback for maintenance of the specified cadence and to complete a maximal effort. During the last 5 s of each stage, HR and ratings of perceived exertion (RPE; 6–20 scale) (Borg 1982) were recorded. HR and RPE were recorded at volitional exhaustion and further blood lactate concentration samples were taken upon completion of exercise and 5 min postexercise. $W_{\text{peak}}$ was calculated as the mean power achieved during the final minute of the test (Lamberts et al. 2012). If exhaustion occurred less than 1 min into a stage, the appropriate duration undertaken at each power output was used to calculate a pro-rata $W_{\text{peak}}$ (Higgins et al. 2013a).

**Experimental trials**

After 5 min of seated rest, HR, perceived readiness to exercise (PRE), abdominal discomfort (AD), and gut fullness (GF; Higgins et al. 2013a) were recorded. A finger-prick capillary blood sample was collected and analysed for blood lactate concentration as previously described. A second capillary blood sample was then collected in a 100-$\mu$L clininate (Radiometer Medical ApS, Copenhagen, Denmark), capped at both ends and mixed well. Samples were then analysed for pH, base excess, and bicarbonate ion concentration using a blood gas analyser (ABL5 radiometer, Radiometer Medical ApS).

After baseline measurements were completed the participant consumed the experimental solution within the first 5 min of the 60-min pre-exercise period. Participants remained seated throughout and were allowed to consume water ad libitum to minimise GI discomfort. The mean volume of water consumed was monitored and was similar between treatments: CAF ($n = 11$): 251 ± 205 mL, BIC ($n = 12$): 268 ± 157 mL, BIC-CAF ($n = 11$): 381 ± 220 mL, and PLA ($n = 10$): 236 ± 158 mL ($n =$ number of measurements analysed per treatment). PRE, AD, and GF were recorded at 30 and 60 min following ingestion. Approximately 45 min following treatment ingestion, participants were linked to the gas analysis system and expired gas was continually monitored and values for $V_{\text{E}}$, $V_{\text{O2}}$, and RER were subsequently calculated. Baseline data were averaged over the last 60 s of the rest period and for the last 10 s of exercise. At 60 min following treatment ingestion, HR was recorded and further blood samples taken for blood lactate concentration, pH, base excess, and bicarbonate ion concentration. Subsequently each participant completed the $T_{\text{LIM}}$ test at 100% $W_{\text{peak}}$. The $T_{\text{LIM}}$ test commenced with a warm-up consisting of cycling at 70 r min$^{-1}$ for 4 min at 50% $W_{\text{peak}}$, 1 min at 75% $W_{\text{peak}}$ and then 2 min at 70 W (unloaded ergometer). After a verbal countdown the test commenced with participants blinded to the clock throughout. The cadence of 70 r min$^{-1}$ was chosen as research examining a range of power outputs (100–300 W) and cycling cadences (30–120 r min$^{-1}$) during constant load cycling found 70 r min$^{-1}$ to be optimal from both metabolic and respiratory perspectives (Ansley and Cangley 2009). A stationary start was employed, which has previously been used in evaluating high-intensity cycling in a laboratory setting with active but not specifically cycling-trained males, similar to the present study (Wittekind et al. 2011). Ratings of perceived exertion for localised RPE (RPE$_L$), representing the exercising muscles, and overall RPE (RPE$_O$), reflective of cardiovascular strain, were recorded after 1, 2, and 3 min of exercise. AD, GF, and HR were recorded and blood samples taken for blood lactate concentration, pH, base excess, and bicarbonate ion concentration immediately postexercise with final blood samples taken 5 min postexercise. The test was ceased the second time the cadence dropped below 70 r min$^{-1}$ for more than 3 or 4 s or if the participant was unable to reestablish the required cadence within 3 to 4 s (Higgins et al. 2013a). Upon completion of the test, the participant was encouraged to warm-down for 5 min by cycling at 70 W. Familiarisation trials were similar to...
experimental trials but excluded the treatment and subsequent 60-min ingestion period.

Statistical analysis

Statistical analysis was completed using IBM SPSS (IBM Corp., Armonk, N.Y., USA). For all data normality (Shapiro–Wilk) and homogeneity of variance/sphericity (Mauchly) were checked prior to choosing the appropriate parametric or nonparametric statistical tests. In limited instances a parametric test was chosen despite the majority of data not being normally distributed (i.e., RPE, RPE2, and AD). This was decided to minimise the potential for type I error owing to multiple individual (nonparametric) comparisons and/or to ensure consistency and comparable analysis to other similar variables.

Where data were normally distributed this is presented as the mean ± SD. Where data were not normally distributed, this is presented as the median and interquartile range (IQR). The IQR range highlights where the middle 50% of the data lies and is the range between the bottom and top quartiles. Similar to the median, the IQR is appropriate when data are not symmetrically distributed (Whitley and Ball 2002). For any violations of sphericity, degrees of freedom were corrected using Huynh–Feldt (Field 2005). For 2-way repeated-measures ANOVAs, Bonferroni corrections for multiple comparisons were applied. Tukey’s honestly significant difference post hoc analysis was undertaken for interactions by calculating the difference required between means for significance at the minimum level of P = 0.05 (Vincent and Weir 2012). The time points considered for HR and blood variables were pre-ingestion (–60 min), pre-exercise (0 min), and at the end of exercise, and 5 min postexercise. Respiratory data were collected at rest and during the final 10 s of exercise. Values for RPE, and RPE2 were analysed at 1 min. 2 min, and 3 min during exercise and at volitional exhaustion. AD and GF were analysed pre-ingestion, 30 min post-ingestion, pre-exercise (60 min post-ingestion), and at the end of exercise. Finally, PRE was analysed pre-ingestion, 30 min post-ingestion, and pre-exercise (60 min post-ingestion).

Data were analysed and quantified using a mixture of effect sizes (ESs), P values (minimum requirement of P ≤ 0.05) and, where appropriate, 95% CIs. For ANOVA main effects and interactions, the ES is reported as the partial η2 value. Otherwise, for normally distributed data the ES (d) was calculated using the difference in means divided by the pooled SD of the compared trials (Nakagawa and Cuthill 2007). For non-normally distributed data the ES (r) was calculated as Z/s/n (Ivarsson et al. 2013). For non-normally distributed data CIs were calculated as described by Conover (1980).

Results

Preliminary tests

\( V_{O2} \), \( V_{CO2} \), HR, blood lactate concentration, and RPE at the end of the graded incremental exercise test were 3.42 ± 0.35 L·min⁻¹ (46 ± 8 mL·kg⁻¹·min⁻¹), 129.9 ± 14.3 L·min⁻¹, 184 ± 10 beats·min⁻¹, 12.5 ± 3.0 mmol·L⁻¹, and 19 ± 1, respectively (note: \( V_{O2} \) and \( V_{CO2} \) data are n = 12 because of equipment failure during data collection). This data supports the criteria for achievement of valid peak oxygen uptake tests (Bird and Davison 1997). Mean minute peak power output (\( W_{peak} \)) was 230 ± 34 W.

Exercise capacity

Figure 1 highlights TLIM data (median; IQR) for the experimental treatments (CAF: 399 s (350–415 s), BIC: 313 s (284–448 s), BIC-CAF: 367 s (333–402 s), and PLA: 358 s (290–433 s)). With the exception of CAF versus BIC (P = 0.039, r = 0.6) and BIC-CAF versus BIC (P = 0.028; r = 0.6), there were no differences between treatments at the group level. However, there was relatively large inter- and intra-individual variation (Table 1).

Cardiorespiratory variables

A treatment × time interaction (P < 0.001; \( \eta^2 = 0.3 \)) was observed for HR. At the end of exercise, HR for both BIC-CAF (183 ± 11 beats·min⁻¹; P = 0.01; d = 0.7) and CAF (182 ± 11 beats·min⁻¹; P < 0.05; d = 0.6) was greater than for PLA (175 ± 11 beats·min⁻¹). Five-minute post-exercise BIC-CAF (123 ± 10 beats·min⁻¹) was greater than PLA (111 ± 9 beats·min⁻¹; P = 0.01; d = 1.3). BIC (113 ± 9 beats·min⁻¹; P < 0.01; d = 1.0), and CAF (115 ± 10 beats·min⁻¹; P < 0.01; d = 0.8). Main effects for time (P < 0.001; \( \eta^2 = 1.0 \)) were observed for \( V_{O2} \), \( V_{CO2} \), and RER, with mean values at the end of exercise of 3.59 ± 0.70 L·min⁻¹, 134.2 ± 26.8 L·min⁻¹, and 1.11 ± 0.10, respectively.

Blood variables

A treatment × time interaction (P < 0.001; \( \eta^2 = 0.4 \)) was observed for blood lactate concentration. Post hoc analysis revealed that at the end of exercise blood lactate concentration for BIC-CAF (15.8 ± 3.5 mmol·L⁻¹) was greater than PLA (12.6 ± 3.3 mmol·L⁻¹; P < 0.01; d = 0.9) and CAF (13.5 ± 3.4 mmol·L⁻¹; P < 0.01; d = 0.7). In addition, blood lactate concentration for BIC (14.7 ± 3.3 mmol·L⁻¹) was greater than PLA (P < 0.01; d = 0.6). Five-minute postexercise blood lactate concentration for BIC-CAF (15.2 ± 3.7 mmol·L⁻¹) was greater than CAF (12.8 ± 3.2 mmol·L⁻¹; P < 0.01; d = 0.7) and PLA (11.4 ± 3.4 mmol·L⁻¹; P < 0.01; d = 1.1). Finally, BIC (13.7 ± 3.3 mmol·L⁻¹) was greater than PLA (P < 0.01; d = 0.7). Treatment × time interactions were observed for bicarbonate ion concentration (P < 0.001; \( \eta^2 = 0.6 \)), base excess (P < 0.001; \( \eta^2 = 0.5 \)), and pH (P < 0.001; \( \eta^2 = 0.6 \)). Compared with CAF and PLA, acid-base balance significantly increased pre-exercise (60 min post-ingestion) for BIC and BIC-CAF and remained elevated at the end of exercise and 5 min postexercise (Table 2, Fig. 2). Interestingly, pH at 5 min postexercise was greater for BIC compared with CAF (P < 0.01, d = 2.0), BIC-CAF (P = 0.01, d = 0.7), and PLA (P < 0.01, d = 1.6; Fig. 2).

Perceptual variables

There were no differences for PRE over time or between treatments. With the exception of CAF pre-exercise (8 ± 2) and PLA pre-ingestion (6 ± 2), PRE at all time points was 7 ± 2–3 units. In contrast, there were significant main effects for time for RPE1 (P < 0.001, \( \eta^2 = 0.9 \)) and RPE2 (P < 0.001, \( \eta^2 = 0.9 \)). Largely, the...
compared with pre-ingestion (1 ± 1 for all treatments) for CAF and BIC pre-exercise (3 ± 2) and at the end of exercise (3 ± 3). AD was significantly greater for both BIC-CAF and BIC vs. serial ingestion with fixed fluid amounts). In summary, although there appear to be some relatively definitive trends, we suggest an individual approach to supplementa-
tion when examining intra-individual responses. For example, participant 9 reported greater LIM for BIC-CAF versus PLA, and 3 units.

### Table 1. Individual and median differences in $T_{LIM}$ (s) between treatments.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Pre-ingestion</th>
<th>Pre-exercise</th>
<th>End of exercise</th>
<th>5 Min postexercise</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>[HCO$_3^-$] mmol·L$^{-1}$</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAF</td>
<td>25±2</td>
<td>25±2</td>
<td>13±3</td>
<td>13±3</td>
</tr>
<tr>
<td>BIC</td>
<td>25±2</td>
<td>32±1*</td>
<td>18±4*</td>
<td>18±4*</td>
</tr>
<tr>
<td>BIC-CAF</td>
<td>24±2</td>
<td>31±2*</td>
<td>16±4$^{1,1}$</td>
<td>16±4*</td>
</tr>
<tr>
<td>PLA</td>
<td>24±3</td>
<td>24±2</td>
<td>14±3</td>
<td>14±3</td>
</tr>
<tr>
<td><strong>[BE] mmol·L$^{-1}$</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAF</td>
<td>1±1</td>
<td>1±1</td>
<td>−14±3</td>
<td>−14±4</td>
</tr>
<tr>
<td>BIC</td>
<td>1±1</td>
<td>9±1*</td>
<td>−7±4*</td>
<td>−6±5*</td>
</tr>
<tr>
<td>BIC-CAF</td>
<td>0±2</td>
<td>7±2*</td>
<td>−9±4</td>
<td>−7±9*</td>
</tr>
<tr>
<td>PLA</td>
<td>0±2</td>
<td>0±1</td>
<td>−13±4</td>
<td>−13±5</td>
</tr>
</tbody>
</table>

**Note:** Data in bold represent greater than daily variation of 16 s (Higgins et al. 2014). BIC, 0.3 g·kg$^{-1}$ body mass sodium bicarbonate; CAF, 5 mg·kg$^{-1}$ body mass caffeine plus 0.1 g·kg$^{-1}$ body mass sodium chloride; BIC-CAF, 0.3 g·kg$^{-1}$ body mass sodium bicarbonate plus 5 mg·kg$^{-1}$ body mass caffeine; PLA, 0.1 g·kg$^{-1}$ body mass sodium chloride; CI, confidence interval; $T_{LIM}$, time to volitional exhaustion.

Discussion

To the best of our knowledge this is the first study to evaluate the effects of ingesting CAF or BIC individually and in combination (BIC-CAF) on high-intensity cycling capacity at 100% $V_{peak}$ in healthy noncycling trained males. In contrast to our original hypothesis at the group level, ingestion of CAF and BIC individually did not enhance $T_{LIM}$ compared with ingestion of an NaCl placebo (PLA). Such results are in contrast with the previously reported individual ergogenicity of CAF (Simmonds et al. 2010) and BIC (Higgins et al. 2013). Similarly, ingestion of BIC-CAF at the group level did not enhance $T_{LIM}$ compared with PLA or CAF, although $T_{LIM}$ was significantly greater for CAF and BIC-CAF compared with BIC. However, it should be acknowledged that there was reasonably significant inter- and intra-individual variation when comparing treatments (Table 1). For example, although both CAF and BIC-CAF had greater $T_{LIM}$ than BIC at the group level, this was not the case for 4/13 (30%) participants. Moreover, the range of individual responses for those who improved with CAF and BIC-CAF compared with BIC (29 to 170 s and 29 to 280 s, respectively) and those who did not (−95 to 6 s and −163 to 11 s, respectively) was considerable. Similarly, although not significant at the group level, $T_{LIM}$ was enhanced beyond daily variation in 8/13 (70%) participants for BIC-CAF versus PLA. Finally, there was no fixed pattern when examining intra-individual responses. For example, participant 9 reported greater $T_{LIM}$ for CAF versus BIC but not for BIC-CAF. Similarly, participant 1 reported greater $T_{LIM}$ for BIC-CAF versus BIC but not versus PLA. Such inter- and intra-individual variation might not necessarily be obvious when examining the individual responses in Table 1 as they are ordered low to high to allow reporting of 95% CI and median data. In summary, although there appear to be some relatively definitive trends, we suggest an individual approach to supplementation is warranted.

Interestingly, differences between treatments in the present study are virtually opposite to those reported by Kilding et al. (2012), who evaluated a 3-km time trial (TT) cycling performance in trained males. The authors reported that CAF (−1.0%), BIC (−1.2%), and BIC-CAF (−1.2%) substantially improved TT performance compared with PLA. In contrast, differences between CAF and BIC (0.3%), CAF and BIC-CAF (0.2%), and BIC-CAF and BIC (0.0%) were insubstantial. However, both the present study and Kilding et al. (2012) appear to agree that differences between BIC-CAF and CAF are most likely trivial at best. The differences in results in the present study to those of Kilding et al. (2012) versus PLA are likely to be related to differences in training status (untrained vs. trained, respectively), CAF dosage (5 mg·kg$^{-1}$ vs. 3 mg·kg$^{-1}$, respectively), exercise protocol ($T_{LIM}$ vs. 3-km TT, respectively), choice of PLA (taste-matched NaCl vs. corn-flour, respectively), method of treatment ingestion (powder mixed with fluid based on body mass vs. capsules with fixed fluid amount, respectively), and timing of ingestion (single bolus with fluid and treatment related to body mass vs. serial ingestion with fixed fluid amounts). In summary, the results of the present study suggest that at the group level ingestion of 5 mg·kg$^{-1}$ CAF enhances $T_{LIM}$ in healthy noncycling trained males compared with 0.3 g·kg$^{-1}$ BIC, but a PLA might be equally as effective.
As both BIC and PLA contain sodium (Na\(^+\)), it is also plausible that changes in electrolyte balance could have influenced performance, at least in some individuals, as Na\(^+\) is a principal component of extracellular strong ion difference (Badr and Nightingale 2007; Story et al. 2004). Indeed, Siegler and Gleadall-Siddall (2010) reported that ingesting 0.045 g·kg\(^{-1}\) body mass sodium chloride; BIC-CAF, 0.3 g·kg\(^{-1}\) body mass sodium bicarbonate plus 5 mg·kg\(^{-1}\) body mass caffeine; PLA, 0.1 g·kg\(^{-1}\) body mass sodium chloride; T\(_{LIM}\), time to volitional exhaustion.

As both BIC and PLA contain sodium (Na\(^+\)), it is also plausible that changes in electrolyte balance could have influenced performance, at least in some individuals, as Na\(^+\) is a principal component of extracellular strong ion difference (Badr and Nightingale 2007; Story et al. 2004). Indeed, Siegler and Gleadall-Siddall (2010) reported that ingesting 0.045 g·kg\(^{-1}\) body mass sodium chloride; BIC-CAF, 0.3 g·kg\(^{-1}\) body mass sodium bicarbonate plus 5 mg·kg\(^{-1}\) body mass caffeine; PLA, 0.1 g·kg\(^{-1}\) body mass sodium chloride; T\(_{LIM}\), time to volitional exhaustion.

As both BIC and PLA contain sodium (Na\(^+\)), it is also plausible that changes in electrolyte balance could have influenced performance, at least in some individuals, as Na\(^+\) is a principal component of extracellular strong ion difference (Badr and Nightingale 2007; Story et al. 2004). Indeed, Siegler and Gleadall-Siddall (2010) reported that ingesting 0.045 g·kg\(^{-1}\) body mass sodium chloride; BIC-CAF, 0.3 g·kg\(^{-1}\) body mass sodium bicarbonate plus 5 mg·kg\(^{-1}\) body mass caffeine; PLA, 0.1 g·kg\(^{-1}\) body mass sodium chloride; T\(_{LIM}\), time to volitional exhaustion.

As both BIC and PLA contain sodium (Na\(^+\)), it is also plausible that changes in electrolyte balance could have influenced performance, at least in some individuals, as Na\(^+\) is a principal component of extracellular strong ion difference (Badr and Nightingale 2007; Story et al. 2004). Indeed, Siegler and Gleadall-Siddall (2010) reported that ingesting 0.045 g·kg\(^{-1}\) body mass sodium chloride; BIC-CAF, 0.3 g·kg\(^{-1}\) body mass sodium bicarbonate plus 5 mg·kg\(^{-1}\) body mass caffeine; PLA, 0.1 g·kg\(^{-1}\) body mass sodium chloride; T\(_{LIM}\), time to volitional exhaustion.

As both BIC and PLA contain sodium (Na\(^+\)), it is also plausible that changes in electrolyte balance could have influenced performance, at least in some individuals, as Na\(^+\) is a principal component of extracellular strong ion difference (Badr and Nightingale 2007; Story et al. 2004). Indeed, Siegler and Gleadall-Siddall (2010) reported that ingesting 0.045 g·kg\(^{-1}\) body mass sodium chloride; BIC-CAF, 0.3 g·kg\(^{-1}\) body mass sodium bicarbonate plus 5 mg·kg\(^{-1}\) body mass caffeine; PLA, 0.1 g·kg\(^{-1}\) body mass sodium chloride; T\(_{LIM}\), time to volitional exhaustion.

As both BIC and PLA contain sodium (Na\(^+\)), it is also plausible that changes in electrolyte balance could have influenced performance, at least in some individuals, as Na\(^+\) is a principal component of extracellular strong ion difference (Badr and Nightingale 2007; Story et al. 2004). Indeed, Siegler and Gleadall-Siddall (2010) reported that ingesting 0.045 g·kg\(^{-1}\) body mass sodium chloride; BIC-CAF, 0.3 g·kg\(^{-1}\) body mass sodium bicarbonate plus 5 mg·kg\(^{-1}\) body mass caffeine; PLA, 0.1 g·kg\(^{-1}\) body mass sodium chloride; T\(_{LIM}\), time to volitional exhaustion.

As both BIC and PLA contain sodium (Na\(^+\)), it is also plausible that changes in electrolyte balance could have influenced performance, at least in some individuals, as Na\(^+\) is a principal component of extracellular strong ion difference (Badr and Nightingale 2007; Story et al. 2004). Indeed, Siegler and Gleadall-Siddall (2010) reported that ingesting 0.045 g·kg\(^{-1}\) body mass sodium chloride; BIC-CAF, 0.3 g·kg\(^{-1}\) body mass sodium bicarbonate plus 5 mg·kg\(^{-1}\) body mass caffeine; PLA, 0.1 g·kg\(^{-1}\) body mass sodium chloride; T\(_{LIM}\), time to volitional exhaustion.

As both BIC and PLA contain sodium (Na\(^+\)), it is also plausible that changes in electrolyte balance could have influenced performance, at least in some individuals, as Na\(^+\) is a principal component of extracellular strong ion difference (Badr and Nightingale 2007; Story et al. 2004). Indeed, Siegler and Gleadall-Siddall (2010) reported that ingesting 0.045 g·kg\(^{-1}\) body mass sodium chloride; BIC-CAF, 0.3 g·kg\(^{-1}\) body mass sodium bicarbonate plus 5 mg·kg\(^{-1}\) body mass caffeine; PLA, 0.1 g·kg\(^{-1}\) body mass sodium chloride; T\(_{LIM}\), time to volitional exhaustion.

As both BIC and PLA contain sodium (Na\(^+\)), it is also plausible that changes in electrolyte balance could have influenced performance, at least in some individuals, as Na\(^+\) is a principal component of extracellular strong ion difference (Badr and Nightingale 2007; Story et al. 2004). Indeed, Siegler and Gleadall-Siddall (2010) reported that ingesting 0.045 g·kg\(^{-1}\) body mass sodium chloride; BIC-CAF, 0.3 g·kg\(^{-1}\) body mass sodium bicarbonate plus 5 mg·kg\(^{-1}\) body mass caffeine; PLA, 0.1 g·kg\(^{-1}\) body mass sodium chloride; T\(_{LIM}\), time to volitional exhaustion.
In contrast with previous research (Higgins et al. 2013a), there were no significant differences between treatments for RPEa or RPEb, indicating that at the group level differences in RPE do not appear to explain differences in T_LIM. However, mean RPEa for BIC-CAF was 1 unit lower at all time points compared with all other treatments and mean RPEb for BIC-CAF was 1 unit lower compared with all treatments after 1 min T_LIM and 1 unit lower than BIC and PLA after 2 min T_LIM (Table 3). These differences might have contributed to the increased T_LIM for BIC-CAF compared with BIC in some individuals (Table 1).

Mean ratings of AD were significantly greater for both BIC-CAF and BIC at pre-exercise (3 ± 2) and at the end of exercise (3 ± 3) compared with PLA (1 ± 2 and 1 ± 2, respectively). Prima facie, as noted above for CAF and none for PLA. Furthermore, AD was lowest for BIC (Higgins et al. 2013). The effects of sodium bicarbonate (NaHCO3) ingestion on high intensity cycling capacity. J. Sports Sci. 31(9): 972–981. doi:10.1080/0264042.2012.758649. PMID:23236737.


Tallis, J., James, R.S., Cox, V.M., and Duncan, M. 2012. The effect of physiological...


