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The Hyperhydration Potential of Sodium Bicarbonate and Sodium Citrate

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Buffering agents have not been comprehensively profiled in terms of their capacity to influence water retention prior to exercise. The purpose of this investigation was to profile the fluid retention characteristics of sodium bicarbonate (BIC) and sodium citrate (CIT) to determine the efficacy of these buffering mediums as hyperhydrating agents. Nineteen volunteers (13 males and six females; age = 28.3 ± 4.9 years) completed three trials (randomized and cross-over design). For each trial, a baseline measurement of body mass, capillary blood, and urine was collected prior to ingestion of their respective condition (control condition [CON] = 25 ml/kg artificially sweetened water; BIC condition = CON + 7.5 g/L of sodium in the form of BIC; CIT condition = CON + 7.5 g/L of sodium in the form of CIT). The fluid loads were consumed in four equal aliquots (0, 20, 40 and 60 min; fluid intake was 1.972 ± 361 ml [CON]; 1.977 ± 360 ml [BIC]; 1.953 ± 352 ml [CIT]). Samples were recorded at 20 (body mass and urine) and 60 min (blood) intervals for 180 min. Blood buffering capacity (HCO_3^-) was elevated ($p < .001$) in both BIC (32.1 ± 2.2 mmol/L) and CIT (28.9 ± 3.8 mmol/L) at 180 min compared with CON (25.1 ± 1.8 mmol/L). Plasma volume expansion was greater ($p < .001$) in both BIC (8.1 ± 1.3%) and CIT (5.9 ± 1.8%) compared with CON (−1.1 ± 1.4%); whereas, total urine production was lower in BIC and CIT at 180 min (BIC vs. CON, mean difference of 370 ± 85 ml; $p < .001$; CIT vs. CON, mean difference of 239 ± 102 ml; $p = .05$). There were no increases observed in body mass ($p = .9$). Under resting conditions, these data suggest BIC and CIT induce a greater plasma hypervolemic response as compared with water alone.

Keywords: acid–base balance, buffering supplementation, dehydration, hydration

Incorporating blood buffering supplementation strategies have been common practice within certain sports for decades (Carr, Hopkins, et al., 2011; McNaughton et al., 2008; Siegler et al., 2016). A recent International Olympic Committee position statement has supported the efficacy of at least one buffer (sodium bicarbonate [BIC]; Maughan et al., 2018), and a number of reviews have highlighted potential mechanisms of action, effective ingestion strategies, and potential side effects of these buffering mediums (Carr, Hopkins, et al., 2011; Lancha Junior et al., 2015; McNaughton et al., 2016). Briefly, increasing blood buffering capacity may support a number of physiological mechanisms associated with sustaining muscle contractile function, anaerobic metabolism, and motor pathways during prolonged, high-intensity exercise (Siegler et al., 2016). Whether in combination or isolation, supporting these mechanisms during periods of sustained and rapid adenosine triphosphate (ATP) turnover has been shown to attenuate the onset of fatigue and at times improve exercise performance (Carr, Hopkins, et al., 2011; Peart et al., 2012). In practice, and as a means to reduce the incidence of gastrointestinal (GI) symptoms, buffers are often ingested with between 7 and 14 ml/kg body mass (BM) fluid in conjunction with a small amount of carbohydrate (Carr, Slater, et al., 2011). Given the constituents (i.e., sodium [Na^+]) of the most commonly consumed buffers (BIC and sodium citrate [CIT]), it would be reasonable to consider the impact of the additional fluid on body water content or indeed the possibility of incorporating buffering supplementation into hyperhydration strategies.

In compromising thermoregulatory environments, preexercise hyperhydration has been shown to attenuate the onset of cardiovascular-related complications associated with prolonged exercise in the heat when compared with euhydration (Goulet et al., 2006). Such practices often involve the ingestion of approximately 25–30 ml/kg BM fluid around 2–3 hr prior to an event (Goulet et al., 2018; Savoie et al., 2016), allowing time for the large amount of fluid to accumulate in the plasma while excess fluid is excreted in the urine. The ingestion of water alone is relatively ineffective as a hyperhydration strategy as most of the additional fluid is lost as urine (Goulet et al., 2018). However, the addition of ingredients with an osmotic load can enhance water retention by simultaneously increasing plasma osmolality and plasma volume (PV; plasma hypervolemia) and has been shown to reduce urine production (Goulet et al., 2018; Savoie et al., 2016). Traditionally, agents such as glycerol and sodium have been used either in isolation or combination to promote a hyperhydrated condition. However, the source of sodium has not been systematically addressed and may be provided in the form of BIC or CIT, with likely differential effects on blood buffering capacity and GI discomfort.

Sodium has been used preferentially over glycerol to induce hypervolemia while simultaneously avoiding GI discomfort, with studies demonstrating ~4% to 5% expansion in PV after ingesting 164 mmol Na^+/L (Sims, Rehrer, et al., 2007; Sims, Van Vliet, et al., 2007). Intriguingly, the proportion of Na^+ used in these

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studies (~4 g) is slightly less than amounts typically consumed during a BIC or CIT loading protocol (e.g., <5 g Na^+ for a 70 kg individual) (Price & Singh, 2008; Renfree 2007; Siegler et al., 2010; Urwin et al., 2016). Whether or not this discrepancy would manifest into a meaningful influence on PV is unknown as to our knowledge; these buffering agents have not been comprehensively profiled in terms of their capacity to influence fluid retention prior to exercise. In conditions where both buffering supplementation and hyperhydration may benefit performance, such as beginning a "long-finish" earlier in an endurance event (Egger et al., 2014), this combination may be a viable prerace nutritional strategy and warrants further investigation. As such, the purpose of this study was to profile markers of blood buffering and hydration in the blood and urine as well as to document GI discomfort during a 3-hr (180 min) loading period, consistent with contemporary ingestion strategies and common practice.

Methods

Experimental Design

A study overview is provided in Figure 1. This study was part of a larger, multicenter effort initiated by the Australian Institute of Sport to investigate the efficacy of different acute hyperhydration strategies leading up to Tokyo 2020. The two research groups presenting this data set were specifically tasked with the blood buffering component of the study given their research track record in this area. As a result, a combined participant pool completed a total of three trials (two experimental and one control [CON]), each separated by 7–10 days (randomized and partially counterbalanced). The phrase "partially counter-balanced" was used as the three conditions (BIC condition, CIT condition, and CON condition) were organized into six sequences (e.g., Latin Squares Design), however, with 19 participants (and not 18 or 24) were unable to completely counterbalance the trial order. The experimental trials were single-blind and consisted of combinations of sodium in various forms (e.g., BIC and CIT), with the CON being flavored water matched for total fluid volume. All procedures in this study were approved by the respective ethics committees (Australian Institute of Sport Ethics Committee, approval code 20190603; Deakin University Human Research Ethics Committee, approval code 2019-407; and Western Sydney University Human Research Ethics Committee, approval code RH13602) and were conducted in accordance with the Declaration of Helsinki.

Participants

A total of 19 recreationally active individuals ($n = 10$, Deakin University; $n = 9$, Western Sydney University) volunteered (13 males and six females; age = 28.3 ± 4.9 years) and completed the study. An a priori sample size ($n = 12$; power of 0.8, and alpha of .05) was estimated using fluid retention data obtained from Goulet et al. (2018) and the statistical freeware G*Power (version 3.1; Faul et al., 2009). All participants were informed verbally and in writing as to the nature and risks associated with the study, submitted to health screening, and gave their written informed consent. Inclusion criteria were (a) healthy as defined by the health screening questionnaire and (b) body mass index range between 19 and 25 kg/m^2. Exclusion

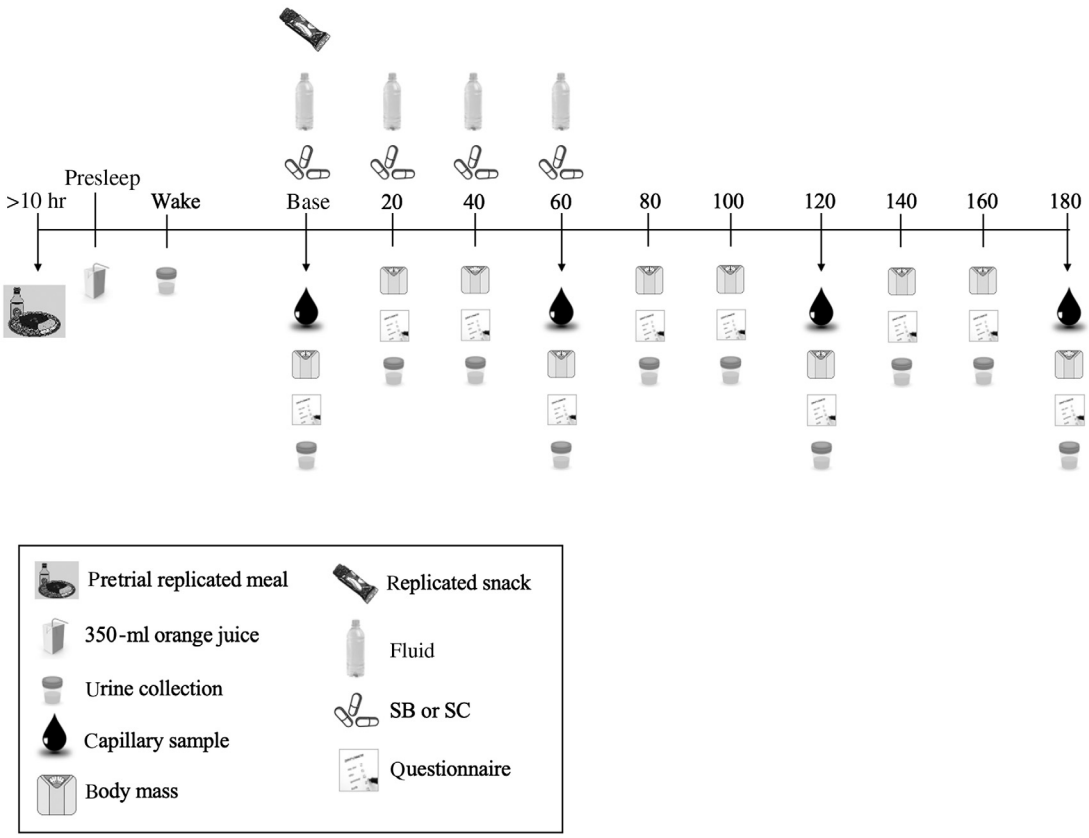


Figure 1 — Study overview. SB = sodium bicarbonate; SC = sodium citrate.

criteria were (a) renal disease, (b) hypertensive, and (c) creatine monohydrate supplementation. All aspects of data collection were completed in the climate-controlled conditions (20.7 °C ± 0.6 °C; 65.2 ± 10.3% humidity) within the Exercise Physiology labs of Deakin University and Western Sydney University.

Experimental Trials

In the evening prior to each trial between 8:00 and 9:00 p.m., all participants consumed 350 ml of orange juice and recorded that night's dinner (completed 10 hr prior to each trial and recorded on the Easy Diet Dietary App™) to standardize food and fluid intake prior to all trials. Participants were also asked to keep to a similar exercise routine the day prior to each trial, to avoid strenuous exercise if possible, and to arrive to the laboratory in an overnight fasted state. On arrival in the morning, participants were asked to completely void their bladder (entire volume measured), and the sample assessed for urine color using an 8-point color scale (Armstrong et al., 1994), which has been reported to have strong correlations with other hydration markers (Perrier et al., 2013). The urine sample was compared with the 8-point scale inside a well-lit laboratory, with the sample transferred into a transparent specimen container (MacFarlane Medical, Surrey Hills, Australia). This sample was also used for the measurement of urine specific gravity (USG; handheld refractometer, Master; ATAGO; JP). A baseline measurement of BM (BC-545 N; Tanita, Arlington Heights, IL) was obtained, and the participants were then asked to sit for 10 min to allow for body fluid stabilization. During this time, a questionnaire, which was adapted with permission from a recently published questionnaire (Gaskell et al., 2019) related to thirst, abdominal comfort, and GI comfort, was completed (Supplementary Material [available online]). Urine assessment, BM measurement, and the questionnaire were completed every 20 min throughout the 180-min trial (Figure 1).

After the 10-min seated period, whole blood was collected in duplicate from the finger-tip into a heparinized 120-µl blood gas capillary tube and immediately analyzed for acid–base status (pH and HCO_3^-) and hemoglobin (i-STAT 1 Wireless, Abbott, Princeton, NJ). Specifically, a lancet was placed on the digit around the outer aspect of the fingerprint to avoid the top and central part of the digit and to obtain optimal blood flow and avoid nerve damage. The first blood droplet was wiped away, and the finger was gently massaged but not squeezed to avoid interstitial fluid leaking into the blood. The second blood droplet was slowly drawn into the capillary tube for immediate sampling. Duplicate collections in 75 µl heparinized tubes were also obtained and centrifuged to determine hematocrit (Thermoline Scientific, Wetherill Park, Australia). Thereafter, blood samples were obtained at 60, 120, and 180 min of the trial (Figure 1).

Once all baseline blood samples were obtained, a timer was started, and participants consumed a standardized snack (two pieces of wholegrain toast with 7 g butter and 14 g jam) concurrently with the supplement for the BIC and CIT trials (see Supplement Interventions). The total amount to be consumed (in grams) was evenly divided into four aliquots and subsequently distributed in 1-g gelatine capsules during baseline, 20, 40, and 60 min ingestion periods (Figure 1). In all conditions, the same artificially sweetened water was administered, allowing for taste, color, and texture to be matched. At the same time, participants started the fluid ingestion regimen which required a total of 25 ml/kg fluid consumed in four aliquots at Time 0 (baseline with snack), 20, 40, and 60 min. In all trials, the 25 ml/kg fluid (chilled at 4 °C) consisted of artificially sweetened water (Cottee's Raspberry or Lemon Cordial, Australia). The 25 ml/kg fluid portion on its own was also considered as the CON.

Supplement Interventions

For the BIC and CIT trials, a target of 7.5 g/L of salt (NaCl) was set based on previous literature (Savoie et al., 2016). In order to equilibrate the Na^+ concentration of NaCl and the BIC/CIT trials, the total amount of Na^+ in 7.5 g/L NaCl was initially determined by taking the total fluid to be consumed by the participant (25 ml/kg) and multiplying it by the fractional equivalent of Na^+. For example, a 70 kg participant would require a total fluid load of 1,750 ml and a total of 13.1 g of NaCl (1.75 L × 7.5). The proportion of Na^+ in that amount would equate to 5.1 g (13.1 × 0.39), as Na^+ represents 39% (or 0.39) of the molecular weight of NaCl (58.4 g/mol). As the amount of Na^+ in BIC and CIT is 27% (assuming 1 mol BIC is 84 g/mol and CIT is 258.1 g/mol, respectively), the amount of Na^+ required was divided by 0.27 to obtain a total buffer load (in grams), which was then equally divided into the four aliquots (each aliquot consisting of the prescribed amount contained within 1 g gelatine capsules). Using the same 70 kg participant example, 5.1/0.27 results in 18.9 g of either BIC or CIT, which is slightly less than the 0.3 g/kg BIC and 0.5 g/kg CIT recommended (or 21 g) for increasing blood buffering capacity (Carr, Hopkins, et al., 2011).

Data Analysis

The PV changes were calculated as per Dill and Costill (1974), and accumulated urine and fluid volumes were calculated as per Goulet et al. (2018).

Statistical Analysis

For the experimental trials, descriptive data are presented as mean ± *SD* with all statistical analyses being completed using IBM SPSS Statistics (version 27.0; SPSS Inc., Chicago, IL). Changes in blood (pH and bicarbonate [HCO_3^-]) urine (urine volume, color, and USG), hydration characteristics (BM and PV), and GI discomfort (max scores recorded out of the 18 questions for "upper," "lower," and "other" GI symptoms; Supplementary Material [available online]) throughout the experimental trials were analyzed using a linear mixed-model two-way analysis of variance for repeated measures. When significant time, condition, or interaction effects were detected, multiple post hoc pairwise comparisons were made using a Bonferroni procedure. Mean differences and *SE* between conditions as well as 95% confidence intervals (CIs) were calculated when significant changes were observed. Two-tailed statistical significance was accepted at $p < .05$.

Results

Baseline Hydration and Fluid Intake

There were no differences between CON, BIC, or CIT conditions at baseline for USG ($p = .99$), urine color ($p = .60$), or BM ($p = .99$) (Table 1). There was also no difference in total fluid intake across the conditions ($p = .99$; Table 1).

Blood Acid–Base Balance and PV

As expected, pH in the BIC and CIT conditions increased over the 180 min as verified by a significant Condition × Time interaction ($F = 12.7$; $p < .001$). Post hoc comparisons indicated BIC was

Table 1 Baseline Hydration Characteristics and TFI

	USG	UC	BM	TFI
CON	1.020 ± 0.008	4.4 ± 1.4	79.1 ± 14.4	1.972 ± 361
BIC	1.019 ± 0.007	4.8 ± 1.3	78.1 ± 14.1	1.977 ± 360
CIT	1.019 ± 0.008	4.3 ± 1.2	80.4 ± 15.3	1.953 ± 352

Note. CON = control; BIC = sodium bicarbonate; CIT = sodium citrate; USG = urine specific gravity; UC = urine color (in arbitrary units); BM = body mass (in kilograms); TFI = total fluid intake (in milliliters).

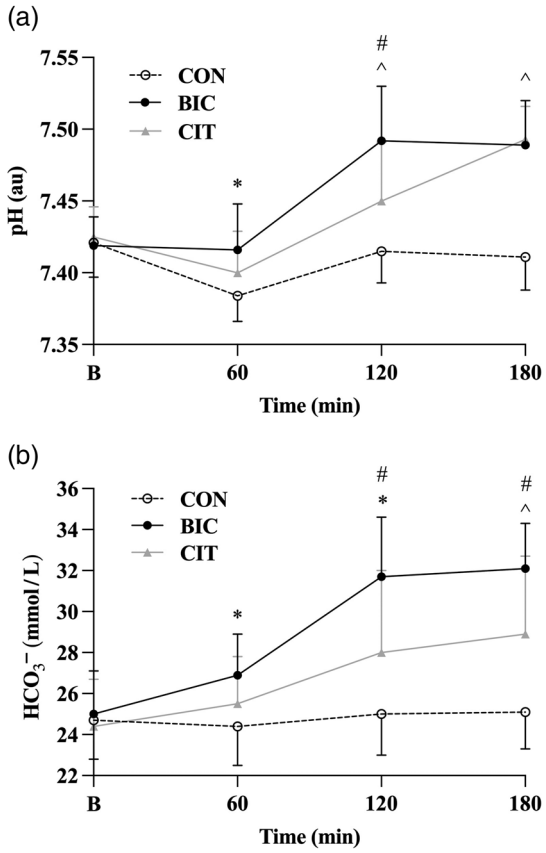


Figure 2 — (a) Whole blood pH and (b) blood bicarbonate obtained at B, 60, 120, and 180 min for each condition. CON = control; BIC = sodium bicarbonate; CIT = sodium citrate; au = arbitrary units; B = baseline. *BIC higher than CON ($p < .001$). ^BIC and CIT higher than CON ($p < .01$). #BIC higher than CIT ($p < .001$).

significantly higher than CON at 60 min (mean difference of 0.03 ± 0.01 au, 95% CI [0.01, 0.05] au; $p < .001$; Figure 2a), then both BIC and CIT elevated compared with CON at 120 min (BIC vs. CON, mean difference of 0.08 ± 0.01 au; 95% CI [0.06, 0.10] au; $p < .001$; CIT vs. CON, mean difference of 0.03 ± 0.01 au; 95% CI [0.01, 0.06] au; $p < .01$; Figure 2a), and 180 min (BIC vs. CON, mean difference of 0.08 ± 0.01 au; 95% CI [0.06, 0.10 au]; $p < .001$; CIT vs. CON, mean difference of 0.08 ± 0.01 au; 95% CI [0.06, 0.11 au]; $p < .001$; Figure 2a). Similarly, HCO_3^- increased in BIC and CIT ($F = 12.7$; $p < .001$), with post hoc comparisons indicating BIC was elevated compared with CON at 60 min (mean difference of 2.4 ± 0.7 mmol/L; 95% CI [0.7, 4.1] mmol/L; $p < .01$), 120 min (mean difference of 6.8 ± 0.7 mmol/L; 95% CI [5.1, 8.4] mmol/L; $p < .001$), and 180 min (mean difference of 7.0 ± 0.7 mmol/L; 95% CI [5.3, 8.7] mmol/L; $p < .001$; Figure 2b). The CIT was only significantly elevated above CON at 180 min (mean difference of 4.8 ± 0.8 mmol/L; 95% CI [2.8, 6.8] mmol/L; $p < .01$; Figure 2b).

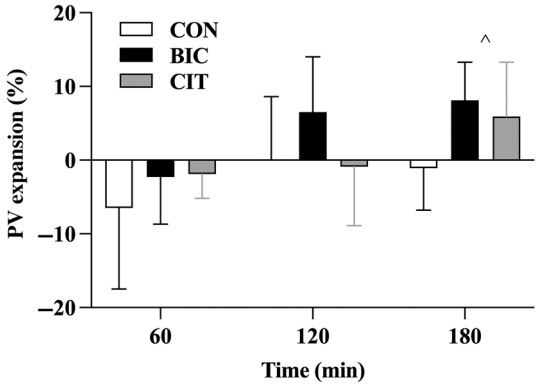


Figure 3 — The PV changes observed at 60, 120, and 180 min for each condition. CON = control; PV = plasma volume; BIC = sodium bicarbonate; CIT = sodium citrate. ^BIC and CIT higher than CON ($p < .05$).

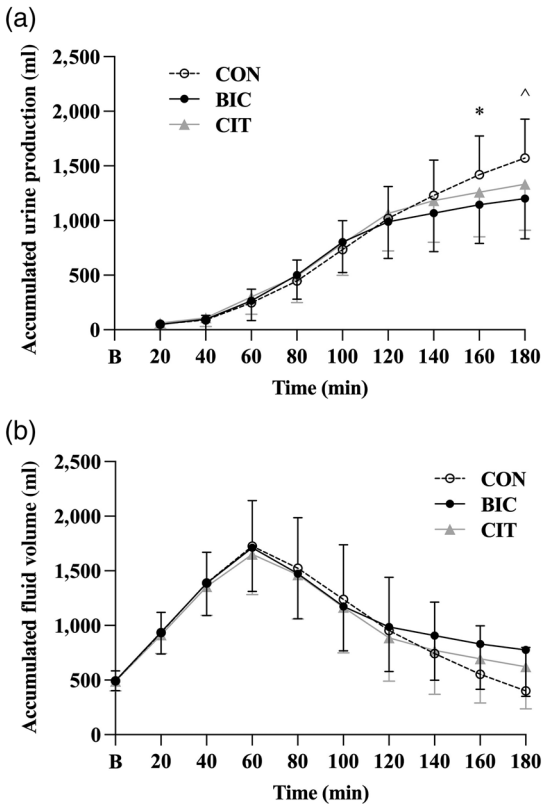
Plasma volume changes were only compared at 180 min in order to determine fluid shifts at the end of the hyperhydration protocol. As such, condition effects were evident demonstrating greater overall PV expansion in both BIC (8.1 ± 1.3%) and CIT (5.9 ± 1.8%) compared with CON (−1.1 ± 1.4%) conditions ($F = 12.6$; $p < .001$; Figure 3).

Urine Production, Accumulated Fluid Volume, and BM

Urine production increased in all conditions from 20 to 180 min (mean accumulated increase of 1.314 ± 56 ml, 95% CI [1.135, 1.493] ml; $p < .001$). There was also a significant Condition × Time interaction ($F = 1.77$; $p = .03$), with post hoc comparisons indicating a significantly lower accumulated urine production with BIC compared with CON at 160 min (mean difference of 274 ± 85 ml; 95% CI [71, 477]; BIC, 14.7 ± 4.6 ml/kg, and CON, 18.3 ± 4.7 ml/kg at 160 min; $p < .01$; Figure 4a) and both BIC and CIT significantly lower than CON at 180 min (BIC vs. CON, mean difference of 370 ± 85 ml, 95% CI [167, 573] ml; BIC, 15.4 ± 4.7 ml/kg, and CON, 20.2 ± 4.3 ml/kg at 180 min; $p < .001$; CIT vs. CON, mean difference of 239 ± 102 ml; 95% CI [6, 484] ml; CIT, 17.1 ± 5.1 ml/kg, and CON, 20.2 ± 4.3 ml/kg at 180 min; $p = .05$; Figure 4a). Accumulated fluid volume increased in all conditions until the 60 min time point (mean increase of 1,204 ± 77 ml; 95% CI [950, 1,458] ml; BIC, 21.6 ± 2.4 ml/kg, CIT, 21.1 ± 2.3 ml/kg, and CON, 21.7 ± 1.9 ml/kg at 60 min; $p < .001$; Figure 4b), then declined significantly until 120 min (mean decline of 503 ± 77 ml; 95% CI [251, 758] ml; BIC, 21.6 ± 2.4 ml/kg, CIT, 21.1 ± 2.3 ml/kg, and CON, 21.7 ± 1.9 ml/kg at 120 min; $p < .001$; Figure 4b). Accumulated fluid volume continued to decline until 180 min in all conditions (mean decline from 120 min of 343 ± 77 ml; 95% CI [89, 569] ml; BIC, 9.6 ± 4.7 ml/kg, CIT, 7.9 ± 5.1 ml/kg, and CON, 4.8 ± 4.3 ml/kg at 180 min; $p < .001$; Figure 4b). There were no significant increases observed in BM across the trial ($p = 1.0$) or between conditions ($p = .9$).

Urine Specific Gravity and Urine Color

The USG declined in all conditions until reaching a nadir between 60 and 100 min (mean decline of 0.014 ± 0.001; 95% CI [0.010,



Figures 4 — (a) Accumulated urine production and (b) accumulated fluid volume recorded over the 180-min protocol and for each condition. CON = control; BIC = sodium bicarbonate; CIT = sodium citrate; B = baseline. *BIC lower than CON ($p < .01$). ^BIC and CIT lower than CON ($p \leq .05$).

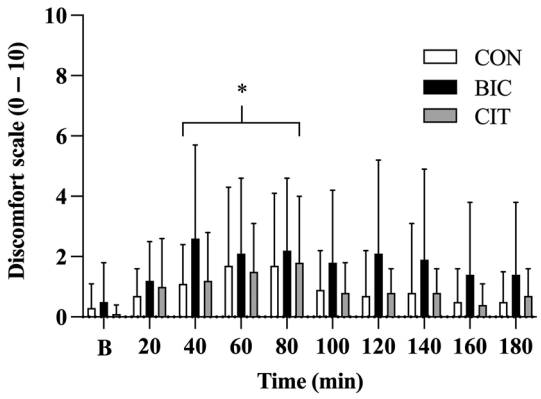


Figure 5 — The GI discomfort (max scores recorded out of the 18 questions for "upper," "lower," and "other" GI symptoms; Supplementary Material [available online]) recorded over the 180-min protocol and for each condition. GI = gastrointestinal; B = baseline; CON = control; BIC = sodium bicarbonate; CIT = sodium citrate. *Higher than B ($p < .05$).

0.018]; $p < .001$). There was a significant Condition × Time interaction ($F = 3.68$; $p < .001$), with post hoc comparisons indicating a difference between BIC and the CIT and CON conditions at 140 min (BIC vs. CON, mean difference of 0.010 ± 0.002; 95% CI [0.006, 0.014]; $p < .001$; BIC vs. CIT, mean difference of 0.007 ± 0.002; 95% CI [0.002, 0.012]; $p < .01$), then both BIC and CIT being different to CON at 160 min (BIC vs. CON, mean difference of 0.009 ± 0.002; 95% CI [0.004, 0.013]; $p < .001$; CIT vs. CON, mean difference of 0.006 ± 0.002; 95% CI [0.001, 0.011]; $p = .03$), and 180 min (BIC vs. CON, mean difference of 0.007 ± 0.002; 95% CI [0.003, 0.012]; $p < .001$; CIT vs. CON, mean difference of 0.007 ± 0.002; 95% CI [0.002, 0.012]; $p < .01$).

Following a similar pattern, urine color also became lighter in all conditions until 80 min (mean change of 3.5 ± 0.2 au; 95% CI [2.9, 4.1] au; $p < .001$). There was also a significant Condition × Time interaction ($F = 3.51$; $p < .001$), with post hoc comparisons indicating a difference between BIC and CON conditions at 140 min (mean difference of 1.1 ± 0.3 au; 95% CI [0.4, 1.7] au; $p < .001$), then both BIC and CIT being different to CON at 160 min (BIC vs. CON, mean difference of 1.5 ± 0.3 au; 95% CI [0.8, 2.2] au; $p < .001$; CIT vs. CON, mean difference of 1.2 ± 0.4 au; 95% CI [0.3, 2.1] au; $p < .01$) and 180 min (BIC and CON, mean difference of 1.4 ± 0.3 au; 95% CI [0.7, 2.1] au; $p < .001$; CIT vs. CON, mean difference of 1.6 ± 0.3 au; 95% CI [0.7, 2.4] au; $p < .001$).

GI Discomfort

A main effect of time ($F = 2.9$; $p < .01$) and condition ($F = 10.6$; $p < .001$) was evident for the combined self-rating GI discomfort scores (max scores recorded out of the 18 questions for "upper," "lower," and "other" GI symptoms). Post hoc comparisons indicated a difference between baseline and 40, 60, and 80 min (mean increase at 80 min of 1.6 ± 0.4 au; 95% CI [0.3, 2.9] au; $p < .01$). The BIC condition induced the greatest amount of discomfort when compared with CON and CIT (BIC vs. CON, mean difference of 0.8 ± 0.2 au; 95% CI [0.4, 1.3] au; $p < .001$; BIC vs. CIT, mean difference of 0.8 ± 0.2 au; 95% CI [0.2, 1.4] au; $p < .01$; Figure 5).

Discussion

The practice of hyperhydration requires a regimented and sustained period of fluid intake, similar to the practice of exogenously increasing blood buffering capacity. Given the potential for combining these two nutritional strategies, the primary purpose of this study was to examine the effect of sodium in the form of BIC and CIT versus water alone on indices of hydration. A secondary aim was to profile any corresponding changes in blood buffering capacity between BIC and CIT during the ingestion period (180 min). Our findings demonstrate a more pronounced shift in PV in both BIC and CIT, approximately 8% and 6% increase, respectively, after 180 min when compared with water (CON). The acute changes in PV were not reflected in measures of total body water, as there was no difference observed in either accumulated fluid volume or BM across the three conditions. Finally, although blood buffering capacity increased significantly in both BIC and CIT throughout the 180 min, the rise was attenuated in the CIT condition and ultimately reflected in a smaller overall increase in blood bicarbonate (~7 mmol/L [BIC] and ~5.5 mmol/L [CIT]).

To our knowledge, there are only a small number of studies that have investigated the potential for introducing BIC or CIT for the purpose of hydration. Of these, the focus has been exclusively on examining their efficacy as rehydrating agents under conditions of acute dehydration (Kupcis et al., 2012; Suvi et al., 2018; Timpmann et al., 2012). In 2012, Timpmann et al. investigated the effects of introducing 600 mg/kg BM into a 16-hr recovery period in trained wrestlers simulating a rapid BM loss protocol of

5% (a technique commonly employed to make weight prior to competition; Timpmann et al., 2012). Sodium citrate was consumed in three separate periods during the 16-hr recovery (200 mg/kg BM during an initial recovery meal, 1 hr prior to bed and breakfast the next morning). Food intake during the recovery period was prescribed, whereas water consumption was ad libitum (albeit similar between conditions [~5,150 vs. 5,330 ml]). The authors observed no differences in indices of hydration between the CIT and placebo control (wheat flour) groups over the 16-hr recovery period, as USG increased significantly during the weight loss period (~1.018 to 1.029) but normalized by the end of the recovery period (~1.011) in both conditions. After an approximate 7% decline in PV during the acute dehydration period, the relative change after 16 hr of recovery in the CIT condition exceeded that of the placebo group (~18% vs. 9%; Timpmann et al., 2012). This absolute increase in PV in the CIT condition nearly doubles the changes observed in the present study (~11% vs. 6%). In a follow-up study where the authors induced a 4% loss in BM followed by 16-hr recovery and 40-km cycling time trial, they observed a greater volume of water consumption (again ad libitum) in the CIT condition (~3,360 vs. 2,850 ml) during recovery (Suvi et al., 2018). This observation was also accompanied by a larger overall change in PV and increase in BM, again in the CIT condition (Suvi et al., 2018). Although obvious differences in study designs exist (e.g., exercise-induced dehydration, ad libitum fluid intake, recovery time periods), collectively the persistent increase in PV after CIT ingestion is higher but consistent with other studies examining sodium ingestion in isolation (between 4.5% and 5%) (Sims, Rehrer, et al., 2007; Sims, Van Vliet, et al., 2007).

Kupcis et al. investigated the acute effects of BIC ingestion (0.3 g/kg BM) versus placebo control (corn flour) in a cohort of elite lightweight rowers after reducing their BM by 4% in the 24 hr preceding a 2,000 m rowing ergometer time trial (Kupcis et al., 2012). In contrast to the protracted ingestion timeframe of the previous studies (Suvi et al., 2018; Timpmann et al., 2012), BIC was ingested in a more commonly practiced prerace scenario (e.g., split doses 70 and 90 min prior to the time trial) and with a standardized amount of fluid (22.2 ml/kg BM) (Kupcis et al., 2012). Under these conditions, the authors observed only a partial restoration of hydration status prior to the time trial that was similar across both recovery treatments (~4% absolute increase in PV and 1.6 kg increase in BM from weigh-in to prewarm-up, respectively). The authors also noted a greater amount of urine output, albeit nonsignificant, during the ingestion period in the placebo condition (~180 vs. 100 ml), suggesting better fluid retention in the BIC rehydration strategy. In contrast to the present study, although urine production was ultimately lower in the BIC versus CON condition, we did not observe these differences until 160 min into the trial (Figure 3a). The most likely explanation for this discrepancy is the extended ingestion duration of the present study, as both studies had similar total fluid loads (22.2 vs. 25 ml/kg BM). Similarly, PV expansion in the present study was approximately 6% in the BIC condition at roughly the same time period, but by 180 min had reached just over 8%. Collectively, it appears that both BIC and CIT induce PV expansion similar to sodium in isolation and regardless of preingestion losses in BM (e.g., voluntary dehydration).

In contrast to other, more traditionally employed hyperhydrating agents (e.g., sodium and glycerol), the PV expansion observed in both BIC and CIT conditions in the current study (between ~6% and 8%) appears comparable and irrespective of differences in total fluid intake volumes. In two consecutive studies investigating the effects of high Na^+ ingestion (164 mmol Na^+/L or ~3.8 g) prior to exercising in the heat, Sims et al. observed an increase in PV of approximately 4.5% (both males and females) 45–80 min after ingesting the sodium in 10 ml/kg of fluid (Sims, Rehrer, et al., 2007; Sims, Van Vliet, et al., 2007). Using slightly less Na^+ (60 mg/kg of salt), Morris et al. also reported fluid retention rates prior to exercise comparable with the buffering agents in the present study (~550 to 690 ml) (Morris et al., 2015). Glycerol ingestion has only recently re-emerged after being removed from the banned substance list (https://wada-ama.org). Historically researched in isolation (van Rosendal et al., 2010), more recently the hyperhydrating potential of glycerol in combination with salt has been investigated (Goulet et al., 2018; Savoie et al., 2016). In both studies, adding the two mediums together resulted in a PV expansion of nearly 15%; whereas, with each in isolation, the increase was more comparable with the present study (~9% to 10%; Goulet et al., 2018; Savoie et al., 2016). Whether or not glycerol added to either BIC or CIT would result in a similar increase in PV remains to be investigated.

A cursory look into the published literature will reveal a wide variety of ingestion protocols for both BIC and CIT (Carr, Slater, et al., 2011; McNaughton et al., 2008, 2016; Peart et al., 2012; Urwin et al., 2021). As mixing the buffers in solution is often considered unpalatable, most contemporary studies report encapsulating these mediums into either gelatine or enterically coated capsules. Moreover, rapidly ingesting large quantities of BIC (e.g., 0.2–0.4 g/kg BM) or CIT (e.g., 0.7–0.9 g/kg BM) in liquid solution also results in a greater likelihood individuals will experience GI discomfort (Carr, Slater, et al., 2011; Urwin et al., 2016). Nearly a decade ago, Carr et al. profiled GI discomfort in conjunction with changes in blood buffering capacity during eight different BIC ingestion protocols (Carr, Slater, et al., 2011). Both ingestion time frame (30 or 60 min), fluid volume (7 or 14 ml/kg BM) and form (capsules or solution) were manipulated in a repeated-measures design. One additional trial included a meal consisting of 1.5 g/kg BM of carbohydrate, which intriguingly resulted in the lowest incidence of GI symptoms (Carr, Slater, et al., 2011). The results of this study have been widely implemented in professional practice and indeed provided part of the theoretical framework for the present study. Following these guidelines, we have demonstrated that increasing the total fluid volume from 7 to 25 ml/kg BM, a level more commensurate with traditional hyperhydration strategies (Goulet et al., 2018; Savoie et al., 2016), results in similar elevations in blood buffering capacity and minimal GI distress (Figures 2a, 2b, and 5) but also may be an effective strategy to expand PV prior to exercising in challenging environmental conditions. Moreover, as we did not observe any significant changes in BM, the additional fluid should not concern practitioners when considering using this ingestion strategy within sports where small amounts of additional weight may impair performance (e.g., triathlon team relay, middle distance running, mixed-martial arts, boxing, etc.).

As expected, both BIC and CIT conditions increased blood buffering capacity to levels widely considered to be ergogenic (e.g., [HCO_3^-] values between 5 and 7 mmol/L above normal [~25 mmol/L]; Carr, Hopkins, et al., 2011; Heibel et al., 2018; McNaughton et al., 2016; Peart et al., 2012). Although the rate of [HCO_3^-] increase was slower than when BIC is consumed in solution (Price & Singh, 2008; Renfree, 2007; Siegler et al., 2010), the general pattern observed in the BIC condition was comparable with others using similar ingestion protocols (Boegman et al., 2020; Carr, Slater, et al., 2011). A handful of older studies have profiled changes in acid–base balance after CIT ingestion (Kowalchuk et al., 1989; McNaughton, 1990), but these

were ingested in solution and in a fasted state. A more recent body of evidence would suggest time-to-peak increase in [HCO_3^-] after CIT ingestion is often protracted when compared with BIC (Peacock et al., 2021; Urwin et al., 2021). This might explain the discrepancy in the present study, as the relative rise in both pH and HCO_3^- was slower in the CIT condition, compared with BIC, and ultimately lower at 180 min (Figure 2a and 2b). The disparate rates of increase may be a reflection of the different mechanisms of action associated with the two mediums, with BIC directly influencing blood bicarbonate concentrations while CIT, through dissociation into sodium and citrate, indirectly influences the distribution of cations and anions in plasma (Kowalchuk et al., 1989). Alternatively, it may also simply be an effect of matching sodium content across the conditions, which resulted in the absolute concentrations of CIT being lower (~0.3 g/kg BM) than typically ingested amounts (~0.5 to 0.7 g/kg BM) (McNaughton, 1990; Urwin et al., 2016).

There are limitations to be acknowledged within the current investigation and may provide scope for future research. First, although the participant population included a small number of females, logistical and financial constraints did not allow for periodizing the trials to coincide with specific phases of the menstrual cycle. We acknowledge the influence estrogen and progesterone concentrations may have on extracellular volume (Stachenfeld et al., 1999; Stachenfeld & Taylor, 2004), and further, menstrual cycle tracking in the context of hydration monitoring provides an important topic for future research (Giersch et al., 2020). We also did not measure beverage osmolality nor osmolality changes in the blood or urine. These measures could have provided further clarity regarding the practical implementation of these solutions in training or competition, as well as improved our understanding of the fluid distribution throughout the intra- and extracellular matrix. Finally, we acknowledge that the frequency of our measurements (every 20 min, which was required to facilitate the frequency of urine sampling included in our protocol) only provided for 10 min of seated rest prior to capillary sampling, which may have been insufficient to ensure complete redistribution of body water (Shirreffs & Maughan, 1994).

In conclusion, both BIC and CIT appear to increase PV to a greater extent than water alone. This expansion in PV is also accompanied by an increase in blood buffering capacity. In addition, we did not observe any substantial change in BM with the 25 ml/kg BM fluid, which should placate any concern for those athletes involved in weight restricted events. Finally, although GI discomfort was minimal throughout the 180-min trial, symptoms still persisted, and any precompetition hyperhydration strategies need to be designed around the individual tolerability of an athlete. Given the findings of this preliminary study, future research should investigate whether there is practical merit in incorporating these buffers into hyperhydration strategies in an exercise performance context.

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