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The effects of sodium bicarbonate supplementation at individual time-to-peak blood bicarbonate on 4-km cycling time trial performance in the heat

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ABSTRACT

The purpose of this study was to explore the effect of individualised sodium bicarbonate ($NaHCO_3$) supplementation according to a pre-established individual time-to-peak (TTP) blood bicarbonate (HCO_3^-) on 4-km cycling time trial (TT) performance in the heat. Eleven recreationally trained male cyclists (age: 28 ± 6 years, height: 180 ± 6 cm, body mass: 80.5 ± 8.4 kg) volunteered for this study in a randomised, crossover, triple-blind, placebo-controlled design. An initial visit was conducted to determine TTP HCO_3^- following 0.2 g.kg^{-1} body mass (BM) $NaHCO_3$ ingestion. Subsequently, on three separate occasions, participants completed a 4-km cycling TT in the heat (30 degrees centigrade; °C) (relative humidity ~40%) following ingestion of either $NaHCO_3$ (0.2 g.kg^{-1} body mass), a sodium chloride placebo (0.2 g.kg^{-1} BM; PLA) at the predetermined individual TTP HCO_3^-, or no supplementation (control; CON) . Absolute peak [HCO_3^-] prior to the 4-km cycling TT's was elevated for $NaHCO_3$ compared to PLA (+2.8 mmol.l^{-1}; $p = 0.002$; $g = 2.2$) and CON (+2.5 mmol.l^{-1}; $p < 0.001$; $g = 2.1$). Completion time following $NaHCO_3$ was 5.6 ± 3.2 s faster than PLA (1.6%; CI: 2.8, 8.3; $p = 0.001$; $g = 0.2$) and 4.7 ± 2.8 s faster than CON (1.3%; CI: 2.3, 7.1; $p = 0.001$; $g = 0.2$). These results demonstrate that $NaHCO_3$ ingestion at a pre-established individual TTP HCO_3^- improves 4-km cycling TT performance in the heat, likely through enhancing buffering capacity.

Highlights

- This is the first time $NaHCO_3$ ingestion has been shown to improve 4-km cycling TT performance in conditions of high ambient heat.
- A smaller dose of $NaHCO_3$ (0.2 g.kg^{-1} BM) is ergogenic in the heat, which is smaller than the dose typically ingested for sports performance (0.3 g.kg^{-1} BM). This is important, as gastrointestinal discomfort is typically lower as the dose reduces.
- This study suggests that the individualised time-to-peak HCO_3^- ingestion strategy with lower doses of $NaHCO_3$ is an ergogenic strategy in conditions of high ambient heat.

KEYWORDS
Alkalosis; supplements; track cycling; buffering; environmental physiology

Introduction

Athletes who compete indoors or internationally are frequently exposed to warm-hot ambient environments, as such events are commonly held in these climates (e.g. Summer Olympic Games). Equally, many athletes worldwide are required to perform in warm-hot environments during the warmest season, or at the hottest part of the day. This is apparent during indoor track cycling events where temperatures are approximately 28–34°C (depending on the location and ventilation quality); whilst in most cases air conditioning is not available. Indeed, at the most recent Olympic games (Tokyo, 2020) daily temperatures exceeding 30°C were common (Costa, Gaskell, McCubbin, & Snipe, 2020), which creates a greater physiological challenge for the athlete compared to competing in a thermoneutral environment. Specifically, exercise in warm-hot environments causes alterations to muscle energy metabolism, such that in the scenario of high-intensity exercise over 1 min, there is a significant shift in contribution of adenosine triphosphate (ATP) supply from aerobic to anaerobic energetic systems, such as anaerobic glycolysis (Febbraio, 2001; Febbraio, Snow, Stathis, Hargreaves, & Carey, 1994; Fink, Costill, & Van Handel, 1975). Combine this with greater level of extracellular lactate during exercise in the heat versus thermoneutral conditions for the same given exercise, this suggests a greater level of acidosis is present (Robergs, Ghiasvand, & Parker, 2004). Unsurprisingly, Mitchell, Rogers, Basset, and Hubing (2014) reported a significant reduction in exercise capacity (time to exhaustion) in hot environments (37°C) compared to cool environments (10°C) at both 80% and 100% VO_{2max}. It is intuitive to suggest

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therefore that nutritional interventions that could support ATP production via anaerobic energy pathways and reduce acidic stress may mitigate the deleterious physiological changes caused by exercising in the heat.

Sodium bicarbonate ($NaHCO_3$) supplementation is a well-known alkalotic buffer, which can increase circulating blood bicarbonate (HCO_3^-) within the extracellular compartments (typically around 5–6 $mmol.l^{-1}$). Typical dosage is between 0.2 and 0.4 $g.kg^{-1}$ body mass (BM), although a 0.3 $g.kg^{-1}$ BM dose is most widely accepted as being optimal for performance enhancement (McNaughton, Gough, Deb, Bentley, & Sparks, 2016). Whilst some authors suggest acidosis is not a contributor to fatigue (see Westerblad, 2016), ingestion of $NaHCO_3$ is suggested to increase extracellular buffering capacity and therefore improve intramuscular hydrogen cation (H^+) handling. Specifically, upregulation of the lactate-H^+ co-transporter to efflux H^+ from the active musculature into circulation may occur, which subsequently maintains the acid base balance of the intracellular (muscle) compartments (Bishop, Edge, Davis, & Goodman, 2004; Mainwood & Worsley-Brown, 1975). Moreover, as H^+ provides competition at the troponin-binding site, the greater efflux of H^+ from the muscle cytosol caused by $NaHCO_3$ supplementation could facilitate improved cross-bridge cycling (; Knuth, Dave, Peters, & Fitts, 2006). This, in theory, should allow for sustained muscle contractions during high-intensity exercise. Based on these mechanisms, the supplementation of $NaHCO_3$ could support the increased demand for anaerobic energy production that is evident under thermal stress, and in turn, improve exercise performance. Despite this, only Mündel (2018) has investigated $NaHCO_3$ ingestion (0.5 $g.kg^{-1}$ BM) in conditions of ambient heat stress (30°C) and reported that total work done (kJ) was improved in the second bout of two 30 s Wingate tests compared to a placebo (effect size = 0.35; $p < 0.05$). Based on the encouraging findings, it is plausible that the use of $NaHCO_3$ could be ergogenic for other types of performance including, but not limited to, track cycling events.

To date, several studies have reported ergogenic effects of $NaHCO_3$ during a 4-km cycling time trial (TT) when ingestion was aligned with an individualised time-to-peak (TTP) HCO_3^- (Gough, Brown, Deb, Sparks, & McNaughton, 2018; Gough, Deb, Brown, Sparks, & McNaughton, 2019; Gough, Deb, Sparks, & McNaughton, 2018; Gurton, Faulkner, & James, 2021; Hilton, Leach, Hilton, Sparks, & McNaughton, 2020). Some of these studies have also examined the use of 0.2 $g.kg^{-1}$ BM $NaHCO_3$, which elicited almost identical ergogenic benefits compared to the traditionally administered 0.3 $g.kg^{-1}$ BM $NaHCO_3$ dose (Gough et al., 2019; Gough, Brown, et al., 2018; Gough, Deb, et al., 2018). Indeed, Gough, Deb, et al. (2018) reported no difference in time to complete a 4-km cycling TT between these two doses (Hege's g effect size (g) = 0.02, $p = 0.870$), whilst both were significantly faster than the placebo (g 0.2 $g.kg^{-1}$ BM = 0.64, g 0.3 $g.kg^{-1}$ BM = 0.66; both $p < 0.05$). Considering that smaller doses of $NaHCO_3$ lead to lower gastrointestinal (GI) discomfort and sodium load (Gough, Deb, Sparks, & McNaughton, 2017; Gurton, Gough, Sparks, Faghy, & Reed, 2020), and that track cyclists are likely to repeatedly supplement $NaHCO_3$ over a few events within 48–72 hours, the smaller dose may be a more attractive option. The aim of this study therefore, was to investigate 0.2 $g.kg^{-1}$ BM $NaHCO_3$ ingestion supplemented at each individuals peak HCO_3^- on 4-km cycling TT performance in conditions of high ambient heat. The hypothesis of this study was that $NaHCO_3$ ingestion would improve 4-km TT cycling performance in the heat compared to the placebo.

Methods

Participants

Eleven male recreationally trained cyclists (de Pauw et al., 2013) (180 ± 6 cm; 80.5 ± 8.4 kg; 28 ± 6 years) volunteered for this study. Whilst a *priori* power calculation was not conducted, our sample size was identical to previous research highlighting $n = 11$ would be required to satisfy statistical power for a 4-km cycling TT, although this study was conducted in thermoneutral conditions (Gough et al., 2019). All protocols were submitted to, and approved by, an institutional review board for testing of human subjects (Gough/3647/Mod/2019/Sep/HELSFAEC), and all participants provided written informed consent prior to any experimental procedure.

Experimental overview

Participants visited the laboratory on five separate occasions in a block randomised, crossover, triple-blind, placebo-controlled study. Each participant was required to record nutritional intake 24 hours prior to laboratory visits and encouraged to maintain identical nutritional ingestion throughout the study. During the initial laboratory visit, a 24-hour dietary recall was conducted, and participants were asked to replicate their intake before subsequent visits to the laboratory. Participants arrived 3 hours post-prandial to each trial, which were conducted at a similar time of day (±1 hour) to manage the effects of circadian rhythms (Reilly, 1990). Trials were separated by a minimum of three days and

maximum of five days to reduce the influence of training adaptations (Drust, Waterhouse, Atkinson, Edwards, & Reilly, 2005). Participants were not ingesting any supplements that could interfere with the results during the study, and none had ingested beta alanine previously.

Pre-experimental procedures

The initial visit involved ingestion of 0.2 g.kg^{-1} BM $NaHCO_3$ (Bicarbonate of Soda, Dr Oatker, United Kingdom) to determine TTP HCO_3^-. Following ingestion of all vegetarian capsules (size 00, Bulk Powders, UK) within a 5 min period, a stopwatch was started, and participants remained seated for 120 min. Finger prick blood samples were collected at baseline in 70µl heparin-coated capillary tubes, following 30 min and subsequently every 15 min using a blood gas analyser (ABL9, Radiometer, Denmark) to analyse blood HCO_3^-. TTP HCO_3^- was determined by the highest HCO_3^- value (absolute-peak) and this established the ingestion timing for each participant during experimental trials. Using a visual analogue scale (Miller et al., 2016), GI discomfort was recorded at baseline and every 15 min until participants reached their respective TTP HCO_3^-. The scale was a 20 cm horizontal line that was anchored with "no symptom" to the left and "severe discomfort" to the right.

Experimental procedures

The following four separate visits involved the completion of a 4-km cycling TT, with one of those visits including a familiarisation trial on a Wattbike cycle ergometer (Nottingham, UK). All trials were conducted in an environmental chamber (Altitude Centre, UK) maintained at 30°C (~40% relative humidity). These conditions were selected, as these were the most commonly reported temperatures upon consultation with track cyclists known to the lead author during pilot work. Participants selected their preferred positions on the Wattbike (i.e. saddle and handlebar) and remained seated (10 min) to accustom to the conditions. Following an individualised warm-up that participants selected based on the knowledge they were preparing for a 4-km TT, participants then passively rested for 5 min and then performed the 4-km cycling TT as quickly as possible. The individualised warm-up was replicated for each experimental trial. This protocol was selected because of its ecological validity and reproducibility (Stone, Thomas, Wilkinson, Gibson, & Thompson, 2011), but also as it would cause sufficient disturbances in acid base balance (Gough, Deb, et al., 2018), thus providing an appropriate protocol to examine the operating mechanisms of $NaHCO_3$.

During each trial, the Wattbike monitor was blinded from the participant, however, verbal encouragement and distance covered was provided. Time to complete (s), mean power (W), and speed (km.h^{-1}) were recorded for the total 4-km distance. Heart rate (HR) (Polar Electro, Finland) and whole-body rating of perceived exertion (RPE) were recorded at rest and every 1 km (scale, 6–20; Borg, 1982). Tympanic temperature was recorded using an infrared tympanic thermometer (Braun ThermoScan® 7 IRT 6520, Braun GmbH, Kornberg, Germany) outside and 10 min in the chamber along with post warm-up and post exercise. Blood measures for acid–base balance (HCO_3^-, and pH) were recorded at baseline, absolute-peak and post-exercise using a blood gas analyser (ABL9, Radiometer Medical Ltd., Denmark). Blood lactate (BLa^-) was also measured (0.3 µl sample) using a portable lactate analyser (Lactate Pro 2, Arkray, Japan) at the same time points. Participants repeated this experimental trial three occasions apart from ingesting either: 0.2 g.kg^{-1} BM $NaHCO_3$, 0.2 g.kg^{-1} BM sodium chloride (placebo; PLA) in vegetarian capsules (size 00, Bulk Powders, UK) or no supplementation (control; CON). Capsules were identical in appearance and the volume of water was recorded and replicated for any subsequent trial (mean = 452 ± 34 ml). A laboratory technician that was not involved in the research had manually prepared and administered the supplementation of $NaHCO_3$ in a block-randomised order to ensure the study remained blinded. Participants remained seated following $NaHCO_3$ or PLA ingestion until their respective absolute-peak, with only water permitted *ab-libitum*. Once this was achieved, participants began their individualised warm-up. Lastly, GI discomfort was recorded every 15 min, as per the previously defined method. At the end of each experimental trial, a supplement belief questionnaire was used to assess the blinding efficacy, as per previous research (Gough, Brown, et al., 2018; Gough, Deb, et al., 2018; Gurton, Macrae, Gough, & King, 2021).

Statistical analysis

All data were assessed for normality using both Shapiro-Wilks tests and graphical methods including skewness and kurtosis. Homogeneity of variance/sphericity were analysed using Mauchly tests and any violations were corrected via Greenhouse-Geisser adjustments. The reproducibility of peak change in HCO_3^- (TTP visit vs. $NaHCO_3$ treatment) and 4-km cycling TT performance (PLA vs CON treatments) was determined using Intraclass Correlation Coefficients (ICC's) and categorised as

poor ($r = \leq 0.40$), fair ($r = 0.40–0.59$), good ($r = 0.60–0.74$) or excellent ($r = \geq 0.74$). One-way repeated measures ANOVA were conducted on 4-km cycling TT performance (completion time, mean power, mean speed). To determine individual changes in time to complete the smallest worthwhile change (SWC) statistic was used (0.2 * between-subject standard deviation; SD) (Paton & Hopkins, 2006). Two-way repeated measures ANOVA were used to analyse blood metabolite responses (HCO_3^-, pH, H^+ and BLa^-), HR, tympanic temperature and RPE. Significant two-way interactions (treatment x time) were explored further by conducting post hoc testing with bonferroni correction factors. The assumption of normal distribution was violated for GI discomfort, therefore Wilcoxon matched-paired signed-rank tests were conducted as the non-parametric alternative, with median and z values reported. For ANOVA interactions and main effects, the effect size is reported as partial eta squared (η_p^2). Between treatment effect sizes (g) were calculated by dividing mean difference by the pooled SD (Nakagawa & Cuthill, 2007) and applying Hedge's g bias correction to account for the small sample size (Lakens, 2013). The interpretations of these effect sizes were categorised as trivial (≤0.2), small (0.2–0.49), moderate (0.5–0.79) or large (≥0.8) (Cohen, 1988). Effect sizes for non-normally distributed data (r) were calculated from $z/\sqrt{n}$, with 0.10, 0.24 and 0.37 considered as small, medium and large, respectively (Ivarsson, Andersen, Johnson, & Lindwall, 2013). Data are presented as Mean ± SD (unless stated otherwise) and 95% confidence intervals (CI) reported for differences in performance, with variances that do not cross the zero-boundary treated as significant (Gardner & Altman, 1986). Statistical significance was set at $p < 0.05$ and all statistical data were analysed using SPSS software version 26 (IBM, Chicago, IL, USA).

Results

4-km Cycling time trial performance

No trial order effect was reported from the performance data (completion time) ($p = 0.972$, $\eta_p^2 = 0.003$). Completion time following $NaHCO_3$ was 5.6 ± 3.2 s faster than PLA (1.6%; CI: 2.8, 8.3; $p = 0.001$; $g = 0.2$) and 4.7 ± 2.8 s faster than CON (1.3%; CI: 2.3, 7.1; $p = 0.001$; $g = 0.2$). In total, six out of eleven participants reported "true" improvements following $NaHCO_3$ ingestion (i.e. change in performance vs. either CON or PLA above the SWC). Excellent reproducibility was observed for completion time between PLA and CON treatments (ICC = 0.998; $p < 0.001$). Mean and inter-individual variation for 4-km completion time is displayed in Figure 1

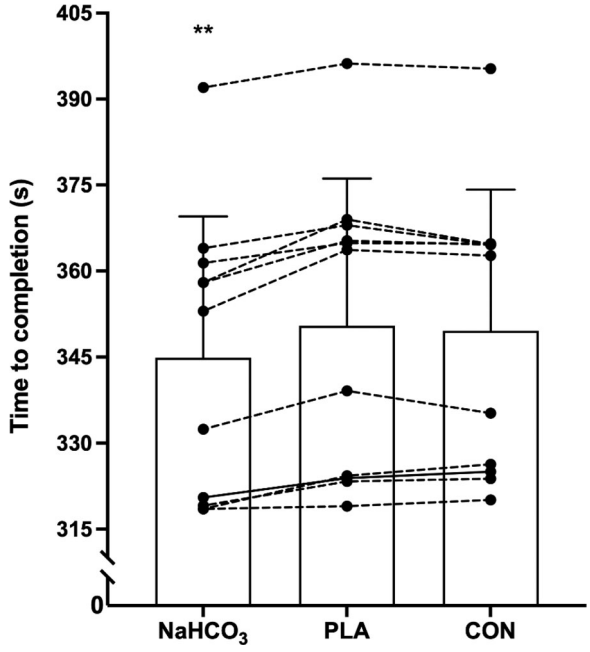

Figure 1. Mean ± SD and inter-individual variation (dashed lines) for 4-km cycling TT completion times in the heat. ** denotes $NaHCO_3$ significantly faster ($p < 0.05$) compared to placebo (PLA) and control (CON).

and Table 1. Only two participants were able to identify the $NaHCO_3$ treatment correctly, with all other participants stating they "don't know".

Mean power across the 4-km distance following $NaHCO_3$ increased by 10.0 ± 7.1 W compared to PLA (+3.6%; CI: 3.9, 16.1; $p = 0.003$; $g = 0.2$) and by 6.7 ± 8.7 W compared to CON (+2.4%; CI: −0.8, 14.3; $p = 0.085$; $g = 0.1$). Mean speed following $NaHCO_3$ was 0.6 ± 0.4 km.h^{-1} higher than PLA (+1.5%; CI: 0.3, 1.0; $p = 0.001$; $g = 0.2$) and 0.5 ± 0.5 km.h^{-1} higher than CON (+1.1%; CI: 0.1, 0.9; $p = 0.025$; $g = 0.2$).

Table 1. Inter-individual differences for changes in 4-km cycling TT performance and absolute increase in [HCO_3^-] from baseline to absolute peak.

	4-km TT performance (s)		Change in [HCO_3^-] (mmol.l^{-1})	
Participant	*$NaHCO_3$ vs. PLA*	*$NaHCO_3$ vs. CON*	*$NaHCO_3$ vs. PLA*	*$NaHCO_3$ vs. CON*
1	**−6.7**	−2.8	5.7	3.6
2	**−11.0**	**−6.7**	0.5	1.1
3	−4.2	−3.3	0.5	0.2
4	**−7.3**	**−6.6**	2.7	2.2
5	**−10.7**	**−9.7**	1.7	1.7
6	**−5.8**	**−7.8**	1.5	0.5
7	−4.0	−0.6	2.1	1.0
8	−3.5	−3.4	3.9	4.1
9	−0.5	−1.6	2.5	2.3
10	−3.4	−4.5	4.8	4.3
11	−4.2	**−4.7**	2.8	2.4

Abbreviations: *HCO_3^-*, blood bicarbonate; *TT*, time trial; *$NaHCO_3$*, sodium bicarbonate; *PLA*, placebo; *CON*, control. Changes in 4-km TT performance highlighted as bold text represent improvements that achieved the smallest worthwhile change (−4.7 s).

Blood metabolite response

During the preliminary TTP visit, absolute change in [HCO_3^-] was 2.6 ± 0.9 mmol.l^{-1} (range, 1.5–4.4 mmol.l^{-1}) and occurred between 30 and 105 min (62.7 ± 19.0 min; CV = 30%). Absolute change in blood pH was 0.04 ± 0.02 AU (range, 0.02–0.07 AU) and occurred between 30 and 105 min (69.5 ± 21.5 min; CV = 31%). These changes in [HCO_3^-] from baseline to peak value displayed excellent reproducibility when compared to absolute change following $NaHCO_3$ during cycling trials (+2.6 mmol.l^{-1}; ICC = 0.976; $p < 0.001$).

Significant treatment × time interactions were observed during the cycling trials for [HCO_3^-] ($p < 0.001$; $\eta_p^2 = 0.628$), blood pH ($p = 0.018$; $\eta_p^2 = 0.359$), [H^+] ($p = 0.022$; $\eta_p^2 = 0.350$) and [BLa^-] ($p < 0.001$; $\eta_p^2 = 0.708$). Absolute peak [HCO_3^-] prior to the 4-km cycling TT's was elevated for $NaHCO_3$ compared to PLA (+2.8 mmol.l^{-1}; $p = 0.002$; $g = 2.2$) and CON (+2.5 mmol.l^{-1}; $p < 0.001$; $g = 2.1$). Peak blood pH was also higher for $NaHCO_3$ compared to PLA (+0.048 AU; $p = 0.007$; $g = 1.9$) and CON (+0.061 AU; $p = 0.055$; $g = 1.1$). Prior to the 4-km cycling TT's, [H^+] was lower following $NaHCO_3$ compared to PLA (−4.5 nmol.l^{-1}; $p = 0.008$; $g = 1.8$) and CON (−6.3 nmol.l^{-1}; $p = 0.099$; $g = 1.0$). Inter-individual differences for the change in [HCO3-] from baseline to peak are displayed in Table 1. Absolute decline in [HCO_3^-] during the 4-km cycling TT's for $NaHCO_3$ was 4.4 ± 3.4 mmol.l^{-1} greater than PLA ($p = 0.005$; $g = 1.8$) and 4.1 ± 2.1 mmol.l^{-1} greater than CON ($p < 0.001$; $g = 2.2$). The total H^+ efflux during the 4-km cycling TT's for $NaHCO_3$ was 7.3 ± 6.7 nmol.l^{-1} higher than PLA ($p = 0.014$; $g = 0.8$) and 12.8 ± 14.6 nmol.l^{-1} higher than CON ($p = 0.047$; $g = 1.0$). Post-exercise [HCO_3^-] was lower following $NaHCO_3$ compared to PLA (−1.5 mmol.l^{-1}; $p = 0.046$; $g = 0.7$) and CON (−1.6 mmol.l^{-1}; $p = 0.01$; $g = 0.9$). Peak [BLa^-] after exercise was elevated following $NaHCO_3$ compared to PLA (+2.76 mmol.l^{-1}; $p = 0.001$; $g = 1.2$) and CON (+2.53 mmol.l^{-1}; $p = 0.002$; $g = 1.1$). There were no differences at any time point between PLA and CON treatments (all $p > 0.05$). Mean ± SD for blood metabolite response is displayed in Figure 2 (A-D).

Heart rate, tympanic temperature and perceived exertion

Significant treatment × time interactions were observed for HR ($p = 0.036$; $\eta_p^2 = 0.196$), but not tympanic temperature ($p = 0.892$; $\eta_p^2 = 0.036$) or RPE ($p = 0.066$; $\eta_p^2 = 0.199$). At the 3-km segment, HR was elevated following $NaHCO_3$ compared to PLA (+5 b.min^{-1}; $p = 0.008$; $g = 0.6$) and CON (+4 b.min^{-1}; $p = 0.053$; $g = 0.5$). Maximum HR at the end of the 4-km cycling TT was elevated following $NaHCO_3$ compared to PLA (+5 b.min^{-1}; $p = 0.027$; $g = 0.7$) and CON (+5 b.min^{-1}; $p = 0.063$; $g = 0.5$).

Gastrointestinal discomfort

Aggregate GI discomfort was exacerbated for $NaHCO_3$ compared to PLA (median, 16 vs. 2 cm) and displayed a large effect size ($z = -2.807$; $p = 0.005$; $r = 0.8$). Severity score for peak GI symptom was higher for $NaHCO_3$ compared to PLA (median, 5 vs. 1 cm) and displayed a large effect size ($z = -2.670$; $p = 0.008$; $r = 0.8$; Table 2).

Discussion

This study aimed to investigate the effects of $NaHCO_3$ ingestion on 4-km cycling TT performance in conditions of high ambient heat. In agreement with the hypothesis, this study reports, for the first time, that $NaHCO_3$ ingestion improves 4-km cycling TT performance in the heat. The current study findings are therefore more applicable to real-world track cycling, which are typically performed in higher temperatures than the thermoneutral conditions used in previous laboratory research. These findings also suggest that exercise of a similar intensity and duration might also benefit from the use of $NaHCO_3$ as an ergogenic strategy (e.g. track and field). Moreover, the current study is the first to demonstrate that an acute, lower dose of $NaHCO_3$ (0.2 g.kg^{-1} BM) is a viable strategy to improve performance in high ambient heat conditions; therefore, corroborating previous findings in thermoneutral conditions (Gough, Brown, et al., 2018; Gough, Deb, et al., 2018). Based on GI discomfort typically being reduced from lower doses of $NaHCO_3$ (i.e. 0.2 g.kg^{-1}) this might be a more attractive option in a practical setting compared to larger doses (i.e. 0.3 g.kg^{-1}) (Gough et al., 2017; McNaughton, 1992). Further research is warranted investigating the use of $NaHCO_3$ ingestion during other exercise modalities that are often conducted in the heat (e.g. Olympic sports).

The current study supports previous research investigating $NaHCO_3$ ingestion in high ambient heat, whereby improvements in performance were observed during the second bout of repeated Wingate tests (2 × 30 s interspersed with 5 min active recovery) following chronic ingestion of 0.5 g.kg^{-1} BM $NaHCO_3$ ingestion split into three equal doses across an eight hour period (Mündel, 2018). Whilst multiple differences in experimental approach between the authors and the current study exist (e.g. ingestion dose and timing, exercise mode and duration), the present study adds novel findings such that $NaHCO_3$ is ergogenic for longer

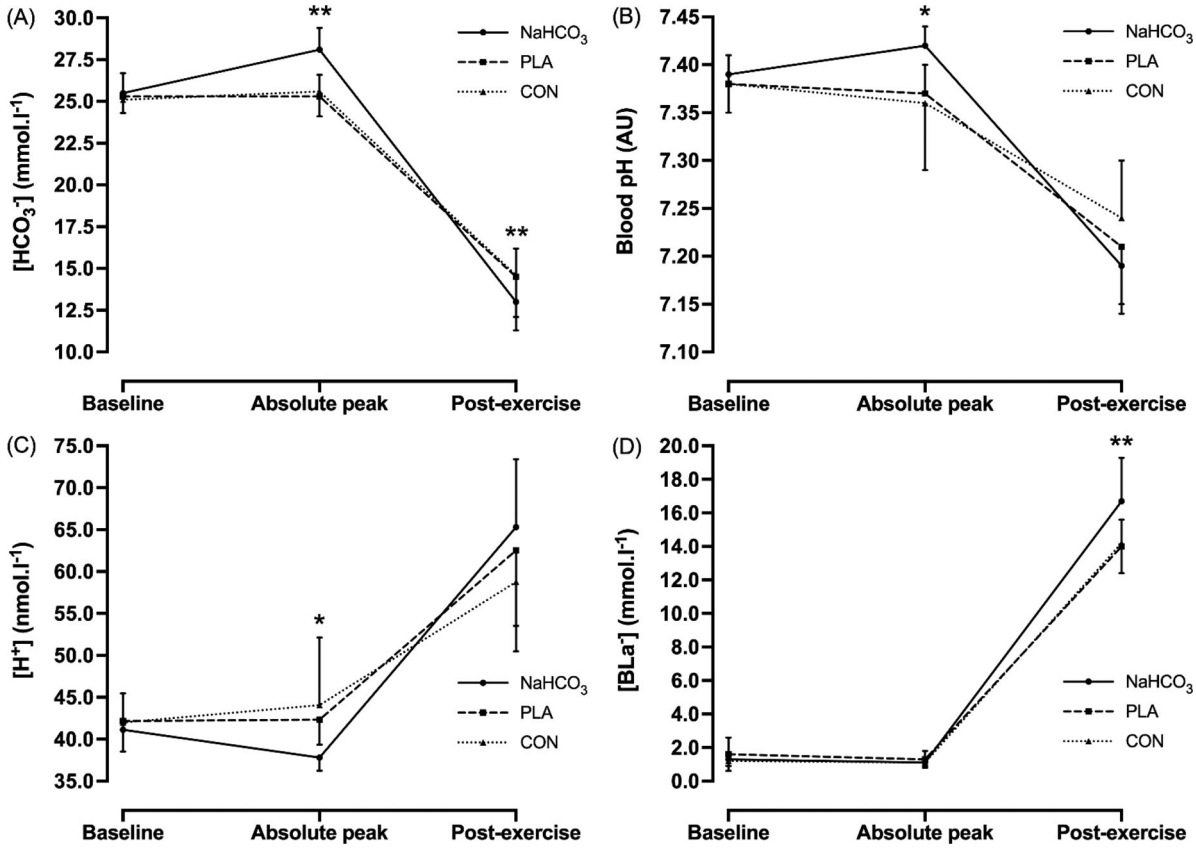

Figure 2. (A-D) Mean ± SD blood metabolite response (A: Blood bicarbonate, HCO_3^-; B: blood pH; C: Hydrogen cations, H^+; D: Blood lactate, BLa^-) from baseline to post-exercise. Some error bars have been removed for clarity. Symbols denote significant difference ($p < 0.05$): * $NaHCO_3$ vs. placebo (PLA); ** $NaHCO_3$ vs. placebo (PLA) and control (CON).

duration exercise in the heat, and arguably within a more ecologically valid protocol (4-km cycling TT vs Wingate). The ergogenic effect in the current study was also more profound compared to the findings of (Mündel, 2018), which may be due to the sub-maximal intensity of the 4-km cycling TT compared to that of the supramaximal intensity Wingate protocol of Mündel (2018). This is due to the potential for supramaximal intensity exercise to cause a rapid decline in pH that completely saturates the monocarboxylate transporter with H^+ and therefore leaving no capacity for $NaHCO_3$ to cause ergogenic effects (Messonnier, Kristensen, Juel, & Denis, 2007). Moreover, the current study offers novelty as a smaller, acute dose of 0.2 g.kg^{-1} BM $NaHCO_3$ was ergogenic despite mild GI discomfort. This corroborates with previous research reporting similar ergogenic effects of smaller $NaHCO_3$ doses during an identical exercise protocol in thermoneutral and hypoxic conditions (Gough et al., 2017; Gough et al., 2019; Gough, Brown, et al., 2018). It is likely that the use of the individualised time-to-peak HCO_3^- strategy ensured the $NaHCO_3$ dose was ergogenic, as previous research using a standardised time point of ingestion (i.e. 60 min prior to exercise for all participants) has shown the 0.2 g.kg^{-1} BM dose was not effective (McNaughton, 1992). Future studies should compare various ingestion strategies and doses to continue optimising the effectiveness of $NaHCO_3$ in environments of high ambient heat, whilst also striving to balance the side effects and performance benefits.

The ergogenic effect of $NaHCO_3$ ingestion on performance in high ambient heat corroborates with findings in thermoneutral environments (Gough, Deb,

Table 2. Peak gastrointestinal (GI) discomfort severity score experienced by each participant during each experimental trial.

Participant	$NaHCO_3$	PLA	CON
1	Belching *(1)*	Bloating *(1)*	Nil *(0)*
2	BUR *(3)*	AD *(2)*	Nil *(0)*
3	Belching *(8)*	Nil *(0)*	Nil *(0)*
4	Belching *(7)*	Nil *(0)*	Nil *(0)*
5	Vomiting *(5)*	Nausea *(2)*	Nil *(0)*
6	Nil *(0)*	Nil *(0)*	Nil *(0)*
7	Belching *(10)*	Vomiting *(9)*	Nil *(0)*
8	Belching *(13)*	AD *(7)*	Nil *(0)*
9	Diarrhoea *(18)*	AD *(2)*	AD *(2)*
10	Belching *(4)*	Nil *(0)*	Nil *(0)*
11	AD *(4)*	Nil *(0)*	Nil *(0)*

Abbreviations: *$NaHCO_3$*, sodium bicarbonate; *PLA*, placebo; *CON*, control; *BUR*, bowel urgency rating; *AD*, abdominal discomfort. Symptom severity score (on a scale of 0–20) is displayed in parenthesis.

et al., 2018), which is surprising given the additional anaerobic demand in the heat that would potentially suggest this supplement would be more ergogenic compared to thermoneutral conditions. Other research supplementing $NaHCO_3$ in hypoxia also display similar findings (Deb, Gough, Sparks, & McNaughton, 2017; Gough et al., 2019; Gough, Brown, et al., 2018), all of which are also more demanding of anaerobic energy production. It is also suggested that pre-exercise increases in plasma volume could be ergogenic in conditions of high ambient heat (Sims, Rehrer, Bell, & Cotter, 2007; Sims, van Vliet, Cotter, & Rehrer, 2007), to which this mechanism should be evident following alkalising agents (Vaher, Timpmann, Aedma, & Ööpik, 2015). Indeed, Vaher et al. (2015) reported following ingestion of sodium citrate (500 $mg.kg^{-1}$) 120 min prior to exercise, plasma volume increased by around 4%. It might have been the short duration of the current studies exercise protocol that nullified any impact of plasma volume, however, as the current study and other published studies to date (Mündel, 2018) employing $NaHCO_3$ supplementation in the heat have ranged from between 30 s to 7 min, whereas this mechanism is more likely relevant to longer duration exercise. Future research could therefore investigate the effectiveness of $NaHCO_3$ ingestion in conditions of heat versus temperate conditions, whilst also using longer duration exercise protocols. This would help identify how far-reaching the ergogenic mechanisms of $NaHCO_3$ ingestion could be in conditions of high ambient heat.

The current study findings support previous work on cycling time trials performed in thermoneutral conditions that report ergogenic effects following $NaHCO_3$ ingestion (Gough, Brown, et al., 2018; Gough, Deb, et al., 2018; Gurton, Faulkner, et al., 2021; Hilton et al., 2020). The rise in extracellular acid base balance likely explains the improved performance following $NaHCO_3$ ingestion, as such increases are suggested to increase H^+ efflux due to the upregulation of the lactate/H^+ cotransporter, and subsequently more H^+ is buffered (Marx et al., 2002). These biochemical changes are suggested to offer protective effects to cross-bridge binding and Ca^{2+} handling (Fitts, 2008, 2016). Support for this can be found from both the significantly increased absolute decline in HCO_3^- during the 4-km cycling TT (i.e. greater amount of extracellular buffering) and the elevated post-exercise lactate for the $NaHCO_3$ versus PLA treatment, which are both indicative of a higher exercise intensity following $NaHCO_3$ ingestion. Equally, the H^+ analysis in the current study corroborates this notion, as this metabolite was lower pre-exercise in the $NaHCO_3$ condition vs. PLA/CON, but was the same at the post-exercise time point, thus inferring a greater H^+ efflux from muscle during the 4-km cycling TT. These findings of the current study must be interpreted with caution as the measurements were only extracellular and therefore, we cannot account for changes at the muscular level. Nonetheless, $NaHCO_3$ ingestion likely improves buffering capacity and will lead to improved exercise performance in most participants.

The increase in HCO_3^- from baseline to absolute peak following $NaHCO_3$ ingestion were low (2.6 ± 0.9 $mmol.l^{-1}$) in comparison to the typical average increase in previous research (Gough et al., 2017; Jones et al., 2016; Renfree, 2007; Siegler, Midgley, Polman, & Lever, 2010). Indeed, Gough et al. (2017) reported the mean increase of HCO_3^- following 0.2 $g.kg^{-1}$ BM $NaHCO_3$ was 5.7 ± 0.9 and 5.6 ± 1.1 $mmol.l^{-1}$ in repeated trials, with 13 out of 15 participants achieving >5 $mmol.l^{-1}$. In fact, in the current study not a single participant reached the 5 $mmol.l^{-1}$ increase from baseline to peak HCO_3^- that is a purported threshold to ensure the ergogenic effect from $NaHCO_3$ ingestion (Carr, Hopkins, & Gore, 2011). Despite this, a significant improvement in performance was reported in this study, and in particular, three participants displayed increases in HCO_3^- of $\leq$2 $mmol.l^{-1}$, however, improved their performance above the SWC of the test protocol. Similarly, one participant reported a 4.5 $mmol.l^{-1}$ increase in HCO_3^-, however did not improve their performance above the SWC. These findings subsequently question the requirement to ingest such large doses of $NaHCO_3$ (Gough et al., 2019), as reaching a threshold increase in HCO_3^- does not seem as important as previous research suggests (Jones et al., 2016; Farias de Oliveira et al., 2020). The reason why such low increases in HCO_3^- were observed might be due to the known inter-individual variation in HCO_3^- changes following $NaHCO_3$ supplementation, and that the current study employed a lower dose of $NaHCO_3$ (Gough et al., 2017; Jones et al., 2016). Future research should attempt to explore reasons why such a large inter-individual variation in bicarbonate uptake occurs (i.e. pre-exercise procedures, training status, genetics), and how this uptake relates to the resulting performance effect.

Conclusion

The ingestion of 0.2 $g.kg^{-1}$ BM $NaHCO_3$ is a suitable ergogenic aid for improving 4-km TT cycling performance in ambient heat. Athletes and coaches can therefore employ this strategy with a degree of confidence that an ergogenic effect will be observed. Lower doses of $NaHCO_3$ may also be attractive due to the lower sodium load and the potential to reduce GI discomfort,

compared to the most commonly ingested 0.3 g.kg^{-1} BM $NaHCO_3$ dose. Future research should explore the use of $NaHCO_3$ in high ambient heat conditions in a range of other competitive events and/or training bouts.

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References

Bishop, D., Edge, J., Davis, C., & Goodman, C. (2004). Induced metabolic alkalosis affects muscle metabolism and repeated-sprint ability. *Medicine and Science in Sports and Exercise*, *36*(5), 807–813.

Borg, G. A. (1982). Psychophysical bases of perceived exertion. *Medicine and Science in Sports and Exercise*, *14*(5), 377–381.

Carr, A. J., Hopkins, W. G., & Gore, C. J. (2011). Effects of acute alkalosis and acidosis on performance. *Sports Medicine*, *41*(10), 801–814.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences*. L. Erlbaum Associates, New York.

Costa, R. J., Gaskell, S. K., McCubbin, A. J., & Snipe, R. M. (2020). Exertional-heat stress-associated gastrointestinal perturbations during Olympic sports: Management strategies for athletes preparing and competing in the 2020 Tokyo Olympic Games. *Temperature*, *7*(1), 58–88.

Deb, S. K., Gough, L. A., Sparks, S. A., & McNaughton, L. R. (2017). Determinants of curvature constant (W′) of the power duration relationship under normoxia and hypoxia: The effect of pre-exercise alkalosis. *European Journal of Applied Physiology*, *117*(5), 901–912.

de Pauw, K., Roelands, B., Cheung, S. S., De Geus, B., Rietjens, G., & Meeusen, R. (2013). Guidelines to classify subject groups in sport-science research. *International Journal of Sports Physiology and Performance*, *8*(2), 111–122.

Drust, B., Waterhouse, J., Atkinson, G., Edwards, B., & Reilly, T. (2005). Circadian rhythms in sports performance—An update. *Chronobiology International*, *22*(1), 21–44.

Farias de Oliveira, L., Saunders, B., Yamaguchi, G., Swinton, P., & Giannini Artioli, G. (2020). Is individualization of sodium bicarbonate ingestion based on time to peak necessary? *Medicine and Science in Sports and Exercise*, *52*(8), 1801–1808.

Febbraio, M. A. (2001). Alterations in energy metabolism during exercise and heat stress. *Sports Medicine*, *31*(1), 47–59.

Febbraio, M. A., Snow, R. J., Stathis, C. G., Hargreaves, M., & Carey, M. F. (1994). Effect of heat stress on muscle energy metabolism during exercise. *Journal of Applied Physiology*, *77*(6), 2827–2831.

Fink, W. J., Costill, D. L., & Van Handel, P. J. (1975). Leg muscle metabolism during exercise in the heat and cold. *European Journal of Applied Physiology and Occupational Physiology*, *34*(1), 183–190.

Fitts, R. H. (2008). The cross-bridge cycle and skeletal muscle fatigue. *Journal of Applied Physiology*, *104*(2), 551–558.

Fitts, R. H. (2016). The role of acidosis in fatigue: Pro perspective. *Medicine and Science in Sports & Exercise*, *48*(11), 2335–2338.

Gardner, M. J., & Altman, D. G. (1986). Confidence intervals rather than P values: Estimation rather than hypothesis testing. *British Medical Journal (Clin Res Ed)*, *292*(6522), 746–750.

Gough, L. A., Brown, D., Deb, S. K., Sparks, S. A., & McNaughton, L. R. (2018). The influence of alkalosis on repeated high-intensity exercise performance and acid–base balance recovery in acute moderate hypoxic conditions. *European Journal of Applied Physiology*, *118*(12), 2489–2498.

Gough, L. A., Deb, S. K., Brown, D., Sparks, S. A., & McNaughton, L. R. (2019). The effects of sodium bicarbonate ingestion on cycling performance and acid base balance recovery in acute normobaric hypoxia. *Journal of Sports Sciences*, *37*(13), 1464–1471.

Gough, L. A., Deb, S. K., Sparks, A. S., & McNaughton, L. R. (2017). The reproducibility of blood acid base responses in male collegiate athletes following individualised doses of sodium bicarbonate: A randomised controlled crossover study. *Sports Medicine*, *47*(10), 2117–2127.

Gough, L. A., Deb, S. K., Sparks, S. A., & McNaughton, L. R. (2018). Sodium bicarbonate improves 4 km time trial cycling performance when individualised to time-to-peak blood bicarbonate in trained male cyclists. *Journal of Sports Sciences*, *36*(15), 1705–1712.

Gurton, W., Macrae, H. Z., Gough, L. A., & King, D. G. (2021). Effects of post-exercise sodium bicarbonate ingestion on acid-base balance recovery and time-to-exhaustion running performance: A randomised crossover trial in recreational athletes. *Applied Physiology, Nutrition, and Metabolism*, *49*(9), 1111–1118.

Gurton, W. H., Faulkner, S. H., & James, R. M. (2021). Effect of warm-up and sodium bicarbonate ingestion on 4-km cycling time-trial performance. *International Journal of Sports Physiology and Performance*, *1*(aop), 1–7.

Gurton, W. H., Gough, L. A., Sparks, S. A., Faghy, M. A., & Reed, K. E. (2020). Sodium bicarbonate ingestion improves time-to-exhaustion cycling performance and alters estimated energy system contribution: A dose-response investigation. *Frontiers in Nutrition*, *7*, 154.

Hilton, N. P., Leach, N. K., Hilton, M. M., Sparks, S. A., & McNaughton, L. R. (2020). Enteric-coated sodium bicarbonate supplementation improves high-intensity cycling performance in trained cyclists. *European Journal of Applied Physiology*, *120*, 1563–1573.

Ivarsson, A., Andersen, M. B., Johnson, U., & Lindwall, M. (2013). To adjust or not adjust: Nonparametric effect sizes,

confidence intervals, and real-world meaning. *Psychology of Sport and Exercise*, *14*(1), 97–102.
Jones, R. L., Stellingwerff, T., Artioli, G. G., Saunders, B., Cooper, S., & Sale, C. (2016). Dose-response of sodium bicarbonate ingestion highlights individuality in time course of blood analyte responses. *International Journal of Sport Nutrition and Exercise Metabolism*, *26*(5), 445–453.
Knuth, S. T., Dave, H., Peters, J. R., & Fitts, R. H. (2006). Low cell pH depresses peak power in rat skeletal muscle fibres at both 30 and 15 C: Implications for muscle fatigue. *The Journal of Physiology*, *575*(3), 887–899.
Lakens, D. (2013). Calculating and reporting effect sizes to facilitate cumulative science: A practical primer for t-tests and ANOVAs. *Frontiers in Psychology*, *4*, 863.
Mainwood, G. W., & Worsley-Brown, P. (1975). The effects of extracellular pH and buffer concentration on the efflux of lactate from frog sartorius muscle. *The Journal of Physiology*, *250*(1), 1–22.
Marx, J. O., Gordon, S. E., Vos, N. H., Nindl, B. C., Gómez, A. L., Volek, J. S., … Kraemer, W. J. (2002). Effect of alkalosis on plasma epinephrine responses to high intensity cycle exercise in humans. *European Journal of Applied Physiology*, *87*(1), 72–77.
McNaughton, L. R. (1992). Bicarbonate ingestion: Effects of dosage on 60 s cycle ergometry. *Journal of Sports Sciences*, *10*(5), 415–423.
McNaughton, L. R., Gough, L., Deb, S., Bentley, D., & Sparks, S. A. (2016). Recent developments in the use of sodium bicarbonate as an ergogenic aid. *Current Sports Medicine Reports*, *15*(4), 233–244.
Messonnier, L., Kristensen, M., Juel, C., & Denis, C. (2007). Importance of pH regulation and lactate/H+ transport capacity for work production during supramaximal exercise in humans. *Journal of Applied Physiology*, *102*(5), 1936–1944.
Miller, P., Robinson, A. L., Sparks, S. A., Bridge, C. A., Bentley, D. J., & McNaughton, L. R. (2016). The effects of novel ingestion of sodium bicarbonate on repeated sprint ability. *The Journal of Strength & Conditioning Research*, *30*(2), 561–568.
Mitchell, J. B., Rogers, M. M., Basset, J. T., & Hubing, K. A. (2014). Fatigue during high-intensity endurance exercise: The interaction between metabolic factors and thermal stress. *The Journal of Strength & Conditioning Research*, *28*(7), 1906–1914.
Mündel, T. (2018). Sodium bicarbonate ingestion improves repeated high-intensity cycling performance in the heat. *Temperature*, *5*(4), 343–347.
Nakagawa, S., & Cuthill, I. C. (2007). Effect size, confidence interval and statistical significance: A practical guide for biologists. *Biological Reviews*, *82*(4), 591–605.
Paton, C. D., & Hopkins, W. G. (2006). Variation in performance of elite cyclists from race to race. *European Journal of Sport Science*, *6*(01), 25–31.
Reilly, T. (1990). Human circadian rhythms and exercise. *Critical Reviews in Biomedical Engineering*, *18*(3), 165–180.
Renfree, A. (2007). The time course for changes in plasma [h+] after sodium bicarbonate ingestion. *International Journal of Sports Physiology and Performance*, *2*(3), 323–326.
Robergs, R. A., Ghiasvand, F., & Parker, D. (2004). Biochemistry of exercise-induced metabolic acidosis. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*.
Siegler, J. C., Midgley, A. W., Polman, R. C., & Lever, R. (2010). Effects of various sodium bicarbonate loading protocols on the time-dependent extracellular buffering profile. *The Journal of Strength & Conditioning Research*, *24*(9), 2551–2557.
Sims, S. T., Rehrer, N. J., Bell, M. L., & Cotter, J. D. (2007). Preexercise sodium loading aids fluid balance and endurance for women exercising in the heat. *Journal of Applied Physiology*, *103*(2), 534–541.
Sims, S. T., van Vliet, L., Cotter, J. D., & Rehrer, N. J. (2007). Sodium loading aids fluid balance and reduces physiological strain of trained men exercising in the heat. *Medicine & Science in Sports & Exercise*, *39*(1), 123–130.
Stone, M. R., Thomas, K., Wilkinson, M., Gibson, A. S. C., & Thompson, K. G. (2011). Consistency of perceptual and metabolic responses to a laboratory-based simulated 4,000-m cycling time trial. *European Journal of Applied Physiology*, *111*(8), 1807–1813.
Vaher, I., Timpmann, S., Aedma, M., & Ööpik, V. (2015). Impact of acute sodium citrate ingestion on endurance running performance in a warm environment. *European Journal of Applied Physiology*, *115*(4), 813–823.
Westerblad, H. (2016). Acidosis is not a significant cause of skeletal muscle fatigue. *Medicine and Science in Sports and Exercise*, *48*(11), 2339–2342.