**Title:** Sodium bicarbonate improves 4 km time trial cycling performance when individualised to time to peak blood bicarbonate in trained male cyclists.

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**Abstract**

The aim of this study was to investigate the effects of sodium bicarbonate (NaHCO3) on 4 km cycling time trial (TT) performance when individualised to a predetermined time to peak blood bicarbonate (HCO3-). Eleven male trained cyclists volunteered for this study (height 1.82 ± 0.80 m, body mass (BM) 86.4 ± 12.9 kg, age 32 ± 9 years, peak power output (PPO) 382 ± 22 W). Two trials were initially conducted to identify time to peak HCO3- following both 0.2 g.kg-1 BM (SBC2) and 0.3 g.kg-1 BM (SBC3) NaHCO3. Thereafter, on three separate occasions using a randomized, double-blind, crossover design, participants completed a 4 km TT following ingestion of either SBC2, SBC3, or a taste-matched placebo (PLA) containing 0.07 g.kg-1 BM sodium chloride (NaCl) at the predetermined individual time to peak HCO3-. Both SBC2 (-8.3 ± 3.5 s; p <0.001, *d* =0.64) and SBC3 (-8.6 ± 5.4 s; p =0.003, *d* =0.66) reduced the time to complete the 4 km TT, with no difference between SBC conditions (mean difference = 0.2 ± 0.2 s; p =0.87, *d* =0.02). These findings suggest trained cyclists may benefit from individualising NaHCO3 ingestion to time to peak HCO3- to enhance 4 km TT performance.

**Key words:** buffering, metabolic alkalosis, dosage, individual pursuit

**Introduction**

Competitive cycling is reflective of high-intensity exercise, particularly in events such as the individual and team pursuit, which entails completion of a 4 km time trial (TT). The typical duration of this event ranges between 4 (world record times) and 7 min (recreational riders), and because of this, a large energy supply is provided by anaerobic glycolysis (Gastin, 2001).

With such a demand an exponential accumulation of metabolites including inorganic phosphate, hydrogen ions (H+), and lactate occurs (Westerblad et al., 2002; Allen et al., 2008). Due to the inverse relationship between H+ and pH, this process causes metabolic acidosis and results in a decrease in blood and muscle pH (Allen et al., 2008). Whilst there is no singular mechanism of peripheral fatigue, perturbations to acid base balance have been implicated to inhibit enzyme activity (e.g. glycogen phosphorylase) and calcium ion (Ca2+) cross-bridge binding (Fitts, 2008, 2016). Preventative strategies such as the ingestion of nutritional ergogenic aids may therefore be beneficial to mitigate such local acid-base disturbances in active musculature (Christensen, Shirai, Ritz, & Nordsborg, 2017; Matson & Tran, 1993).

Ingestion of sodium bicarbonate (NaHCO3), a known buffering agent, can reinforce acid base balance by producing a state of metabolic alkalosis (increased pH and HCO3-) (McNamara & Worthley, 2001). Increases in pH typically result in a greater efflux of H+ and lactate from active musculature into extracellular compartments, due to a greater intra-extracellular gradient, whilst elevated HCO3- can be utilised to buffer against H+ within extracellular compartments (Bishop, Edge, Davis and Goodman, 2004). The resulting effect is more work completed during exercise of high intensities, which in turn, will improve exercise capacity or performance (Bishop et al., 2004; Marx et al., 2002). It is therefore important to heighten the level of blood alkalosis via changes in pH and HCO3- prior to exercise (Gough, Deb, Sparks & McNaughton, 2017a; Jones et al., 2016). Common practice is to prescribe NaHCO3 between a set time of between 60 and 90 mins for all participants (Carr, Hopkins and Gore, 2011; Price and Singh, 2008; Siegler et al., 2009). In a recent study, however, it was reported time to peak HCO3- occurred between 40 and 125 min (Gough et al., 2017a), with a similar variation observed in other dose-response studies (Jones et al., 2016; Miller et al., 2016). Many participants may not therefore achieve peak alkalosis at the start of exercise, which might explain, in part, the lack of an ergogenic effect of NaHCO3 supplemented at 100 min (Correia-Oliveira et al., 2017) and 150 min (Callahan, Parr, Hawley & Burke, 2017) in other 4 km cycling TT studies.

In response to such variation in time to peak alkalosis it is recommended that either time to peak pH or HCO3- is predetermined prior to use for an exercise bout, as this accounts for the inter-individual variation commonly observed (McNaughton et al., 2016; Miller et al., 2016; Jones et al., 2016; Gough et al., 2017c). Indeed, preliminary studies to date have displayed ergogenic benefits of NaHCO3 individualised to a predetermined peak pH in cycling performance (Miller et al., 2016; Deb et al., 2017). Gough et al. (2017a) however, recently demonstrated greater reliability of time to peak HCO3- compared to time to peak pH with Intraclass Correlation Coefficient (ICC) analysis (*r* =0.94 vs. 0.71). It may therefore be more appropriate to determine the effects of NaHCO3 on HCO3- responses, particularly if the athlete wishes to achieve peak alkalosis consistently. Nonetheless, no study to date has investigated the potential ergogenic effects of NaHCO3 supplementation determined by a predetermined individual time to peak HCO3- on an exercise protocol reflective of competitive cycling such as a 4 km TT.

Investigations into the ergogenic effects of individualising NaHCO3 to a predetermined time to peak pH have prescribed an amount of 0.3 g.kg-1 BM (Miller et al., 2016; Deb et al., 2017). This is likely due to early research by McNaughton (1992) reporting a dose-dependent effect on performance, with 0.3 g.kg-1 BM NaHCO3 improving total work done (TWD) to a greater magnitude than 0.2 g.kg-1 during 60 s of maximal cycling; whilst meta-analyses have also shown a meaningful effect on exercise performance following 0.3 g.kg-1 BM NaHCO3 (Peart et al., 2012; Carr et al., 2011). Despite this, there is a paucity of literature investigating the dose-dependent ergogenic effects from smaller doses of NaHCO3 on exercise performance. The greater magnitude of effect between 0.3 g.kg-1 and 0.2 g.kg-1 BM NaHCO3 reported by McNaughton (1992) for instance, was non-significant and only considered one exercise duration/intensity and participant cohort (recreationally active). Furthermore, McKenzie, Coutts, Stirling, Hoeben and Kuzara (1986) reported a negligible 0.3% difference between 0.15 g.kg-1 BM and 0.3 g.kg-1 BM NaHCO3 in a cycling time to volitional exhaustion test at 125% VO2max. Based on such limited evidence, further research is warranted exploring the dose-dependent effects of NaHCO3.

A further concern of a 0.3 g.kg-1 BM NaHCO3 ingestion strategy is the commonly reported gastrointestinal (GI) discomfort symptoms such as stomach cramp, diarrhoea, and in extreme cases, vomiting, which can have major negative implications for exercise performance (Saunders et al., 2014; Gough et al., 2017a, 2017b). It is therefore important to maximise the potential ergogenic effect through attaining peak buffering capacity, whilst also managing the severity of (GI) discomfort. Given that smaller amounts of NaHCO3 (i.e. 0.2 g.kg-1 BM) are associated with lower instances and severity of GI discomfort (Gough et al., 2017a, 2017c), it may be prudent to suggest this amount is a better option practically to the athlete aiming to enhance their performance, as long as ergogenic benefits are still evident.

To heighten the likeliness of an ergogenic benefit and mitigate the severity of GI discomfort, 0.2 g.kg-1 BM NaHCO3 individualised to a predetermined time to peak HCO3- may be suitable. Gough et al. (2017a) reported a 5.7 ± 0.9 mmol.l-1 increase of HCO3- following 0.2 g.kg-1 BM NaHCO3 using a time to peak HCO3- strategy, which is superior to the 3.9 ± 0.9 mmol.l-1 mean change reported in a meta-analysis following a standardised 0.3 g.kg-1 BM NaHCO3 dose (Carr et al., 2011). These changes in acid base balance following 0.2 g.kg-1 BM NaHCO3 are also close to the 6 mmol.l-1 increase purported to lead to an ergogenic effect on performance (Matson & Tran, 1993; Jones et al., 2016). These data combined, suggest 0.2 g.kg-1 BM NaHCO3 individualised to a pre-determined time to peak HCO3- achieves the required acid base balance changes that may improve performance, whilst also reducing the symptoms of GI discomfort. Despite this, no literature to date has investigated the dose-dependent effects (i.e. 0.2 g.kg-1 vs. 0.3 g.kg-1 BM NaHCO3) on exercise performance when individualised to a predetermined time to peak HCO3-. The purpose of this study, therefore, was to investigate the effects of both 0.2 g.kg-1 BM (SBC2) and 0.3 g.kg-1 BM (SBC3) NaHCO3 individualised to a predetermined time to peak HCO3- on 4 km TT performance. We hypothesised that both SBC2 and SBC3 would reduce the time required to complete the 4 km TT.

**Materials and Methods**

***Participants***

A priori power calculation conducted using SPSS Sample Power 3 (IBM, Chicago, IL, USA) displayed a sample size of 11 would allow detection of a 3 s change with high statistical power (β = 0.80; 0.05 = α level). This set criterion was used to detect a difference between NaHCO3 treatments (i.e. SBC2 vs. SBC3) and between SBC treatments and the placebo, as this is the typical difference required to determine medal positions for the men’s individual pursuit and similar events at Olympic Games (Christensen et al., 2017). Eleven male trained cyclists therefore volunteered for this study (height 1.82 ± 0.8 m, body mass 86.4 ± 12.9 kg, age 32 ± 9 years, peak power output (PPO) 382 ± 22 W) with a weekly training frequency of ≥3 times, for a total of ≥5 hours per week, and for a minimum of 2 years training experience, which was specifically in cycling. Based on these descriptors, participants met the criteria of ‘trained cyclist’ as described by De Pauw et al. (2013). Participants were also excluded if they had ingested any nutritional buffers (such as beta alanine) in the prior 6 months of the study. Ethical approval was obtained from the Departmental Research Ethics Committee and each participant provided written informed consent prior to experimental testing.

***Experimental overview***

Participants visited the laboratory on six occasions in a randomised, crossover and double blind designed study (2 x identification of peak blood HCO3-, 3 x cycling TT’s). Constraints on ingestion of alcohol and participation in any strenuous/unaccustomed exercise were in place 24 hours prior to each trial. Caffeine was also prohibited 12 hours prior to any trial. Written logs of nutritional intake were taken, with intake from the first trial replicated for subsequent trials. Participants visited the laboratory in a four-hour postprandial state and trials were conducted at the same time of day to account for circadian rhythms (Reilly, 1990). Experimental trials were separated by at least three days to allow acid base balance variables to return to normal resting concentrations (Siegler et al., 2009).

***Identification of time to peak blood bicarbonate***

On two separate occasions participants ingested either 0.2 g.kg-1 BM NaHCO3 (SBC2) or 0.3 g.kg-1 BM NaHCO3 (SBC3) mixed with 400 ml of water and 50 ml double strength and sugar-free blackcurrant cordial to identify time to peak blood HCO3- and pH. Whilst quietly resting and seated, finger prick capillary blood samples were collected in a 100µl sodium heparin-coated glass clinitube every 10 min for analysis of blood HCO3- and pH over a 120 min period using a blood gas analyser (ABL800 BASIC, Radiometer Medical Ltd. Denmark). The highest HCO3- value was used as a determination of time to peak HCO3- and this determined the timing of ingestion for experimental trials. Supplementation of NaHCO3 was double blinded and randomised (block randomisation), as a laboratory technician outside of the research group prepared the NaHCO3. Likewise, the time to peak HCO3- was determined by researchers outside of the study and the participant was not informed of their time to peak to ensure the double blind nature of the study. For the PLA condition, a time to peak HCO3- was used from either SBC2 or SBC3.

***Four-kilometre cycling protocol, blood measures and perceptual measures***

The next visit involved a familiarisation to the 4 km cycling TT on a Velotron cycle ergometer (Velotron, RacerMate Inc., USA) interfaced with Velotron coaching software (RacerMate Inc., USA). This ergometer has displayed high test-retest reliability with excellent ICC values of between *r* =0.90 to 0.96, p <0.01 for mean power in TT events (Astorino, 2011; Costa, Guglielmo & Paton, 2017). Participants selected a preferred handlebar and saddle position, whilst they were also permitted to change gears freely throughout each TT using their preferred fixed gear ratios. These settings were then adopted for all subsequent trials. Strong verbal encouragement was provided throughout the TT and feedback on the distance covered and cadence was provided via the software (Stone et al., 2011), but time elapsed was blinded. Time to complete, mean power and mean speed was recorded for both the total distance and 0.5 km splits, along with heart rate (HR) every 0.5 km (Polar, T31, Finland). Blood measures for pH and HCO3- were taken pre-ingestion and post-exercise as per the previously described method. A 5µl sample for blood lactate (BLa) was also taken at the same respective time points (Lactate Pro 2, Arkray, Japan). Ratings of perceived exertion (6-20; Borg, 1982) for the whole body (RPEO), legs (RPEL), and affective perceptions of work rate (11-point bipolar scale with +5 representing ‘very good’ and -5 representing ‘very bad’) were recorded every 1 km (Thomas et al., 2015). This procedure was repeated another three times, with the exception that either 0.2 g.kg-1 BM NaHCO3 (SBC2), 0.3 g.kg-1 BM NaHCO3 (SBC3) or a taste matched placebo (PLA) containing 0.07 g.kg-1 BM sodium chloride (NaCl) was ingested, after baseline measures were taken. Participants then sat quietly rested until their respective predetermined time to peak HCO3-, at which point a further blood sample was taken. Treatments were administered in a double-blind manner, and for PLA treatments, a time to peak HCO3- time frame from an SBC treatment was selected randomly by a researcher outside of the study to maintain the double-blind design. Following ingestion, and up to the individuals respective time to peak HCO3-, GI discomfort was measured using a visual analogue scale (VAS) every 10 min, as per previous studies (Miller et al., 2016; Gough et al., 2017a).

**Statistical analysis**

Assessed variables were analysed using both Shapiro-Wilk tests and standard graphical methods for normality, whilst a Mauchly test was used for homogeneity and variance/sphericity. A paired sampled t-test was used to assess the severity and time to peak GI discomfort between SBC treatments. Both mean power and speed were analysed using a repeated measures ANOVA. Otherwise, a two-way repeated measures ANOVA (e.g. condition x each 0.5 km segment/time point) was used and where either interactions or main effects were observed, Bonferroni corrected posthoc pairwise comparisons were carried out. Where main effects or interactions were observed, partial eta squared (*P*η2) effect size is reported. Between treatment effect sizes (*d*) were calculated using the difference in means divided by the pooled SD of the compared trials (Nagakawa & Cuthill, 2007), however with a Hedge’s g bias correction to account for the sample size in this study (Lakens, 2013). All effect size interpretations were considered as trivial (<0.20), small (0.20-0.49), moderate (0.50-0.79) or large (≥0.80) (Cohen, 1988). Intraclass Correlation Coefficients (ICC) were used to determine the reproducibility of blood metabolites (i.e. time to peak HCO3- and pH) following SBC conditions and are reported with *r* value and significance value (p value). Interpretation of reproducibility was determined by the respective *r* value with categories of poor (<0.40), fair (0.40-0.59), good (0.60-0.74) and excellent (>0.74). Data are presented as mean ± SD with 95% confidence intervals (CI) unless otherwise stated. Statistical significance was set at p <0.05 and data were analysed using SPSS v22 for Windows (SPSS Inc., Chicago, IL, USA).

**Results**

***Performance responses for all participants (n =11)***

Faster mean completion times (Figure 1) by 8.3 ± 3.4 s were observed following SBC2 (p < 0.001, CI = 12.0, 4.7, *d* = 0.64) and by 8.6 s ± 5.2 s following SBC3 compared to PLA, respectively (p =0.003, CI = 14.2, 3.0, *d* =0.66). There was no difference between SBC2 and SBC3 (374.0 ± 13.3 vs. 373.7 ± 13.3 s, p =0.87, CI = -3.0, 3.7, *d* =0.02; Figure 1).

\*\*Figure 1 near here\*\*

A 16 ± 13 W (+5.7%) increase in mean power was observed following SBC2 (304 ± 28 W, p =0.02, CI = 2.6, 30.3, *d* =0.62), while in SBC3 an increase of 16 ± 15 W (+5.9%) was observed (304 ± 31 W, p =0.03, CI = 1.1, 32.9, *d* =0.58; Figure 2a) compared to PLA (287 ± 25 W). There was no difference between SBC2 and SBC3 (p =0.90, CI = -10.2, 9.1, *d* =0.01). Following SBC2, a 0.9 ± 0.6 km.h-1 (+2.4%) increase in mean speed was observed compared to PLA (38.6 ± 1.4 vs. 37.7 ± 1.1 km.h-1, p =0.008, CI = 0.2, 1.6, *d* =0.69). Similarly, a 0.8 ± 0.6 km.h-1 (+2.0%) increase in mean speed was observed following SBC3 (38.4 ± 1.3, p =0.02, CI = 0.1, 1.4, *d* =0.56), whilst there was no difference between SBC conditions (p =0.42, CI = -0.3, 0.6, *d* =0.14; Figure 2b).

\*\* Figure 2 near here\*\*

***Performance responses for participants who suffered gastrointestinal (GI) discomfort (n =8)***

Despite the occurrence of GI discomfort, SBC2 improved performance by 9.0 ± 3.8 s in SBC2 (p =0.001, CI = 4.5, 13.5, *d =* 0.68) and 8.9 ± 6.1 s in SBC3 (p =0.02, CI = 1.7, 16.2, *d* = 0.68) compared to PLA. Only one participant failed to improve performance (0.1 s difference vs. PLA), whilst three participants improved by less than the 3 s threshold that was set in the priory power calculation for a meaningful effect (range = 2-2.6 s improvement vs. PLA).

***Blood metabolite responses***

Absolute peak change in HCO3- from baseline was 5.5 ± 0.7 in SBC2 and 6.5 ± 1.3 mmol.l-1 in SBC3 which was not significantly different (p =0.07; *d* =0.92). Peak HCO3- occurred within a range of between 40 to 110 mins in SBC2 (mean 62 ± 20 min, CV: 33%), and between 40 to 100 min in SBC3 (mean 73 ± 20 min, CV: 27%; Figure 3).

\*\*Figure 3 near here\*\*

The change from baseline to the peak pH was not significantly different between SBC conditions (p =0.13, *d =*0.75; SBC2 =0.07 ± 0.02, SBC3 =0.09 ± 0.03). In subsequent cycling trials (i.e. 4km TT’s) good reproducibility was observed for absolute mean change from baseline in pH following both SBC2 (+0.06; ICC *r* =0.67, p =0.026) and SBC3 (+0.06; *r* =0.65, p =0.040). Greater reproducibility was observed for absolute mean change in HCO3- however, displaying excellent reliability in both SBC2 (+4.9 mmol.l-1; *r* =0.86, p =0.002) and SBC3 (+5.6 mmol.l-1; *r* =0.88, p <0.001).

In the cycling trials, a time × treatment interaction was observed for pH (p =0.048, *P*η2 =0.285) whereby pH was +0.07 ± 0.02 (+0.9%) greater at time to peak (figure 4a) for SBC2 (7.46 ± 0.03; p <0.001, CI = 0.09, 0.04, *d* =2.64) and 0.08 ± 0.02 (+1%) greater for SBC3 (7.47 ± 0.02; p <0.001, CI = 0.09, 0.05, *d* =3.85) compared to PLA (7.39 ± 0.02). There was no difference between SBC2 and SBC3 (p =0.69, CI = -0.3, 0.1; *d* =0.38). A time × treatment interaction was observed for HCO3- (p <0.001, *P*η2 =0.796), with values greater following supplementation of NaHCO3 (Figure 4b). At time to peak HCO3-, SBC2 was 5.0 mmol.l-1 ± 1.0 mmol.l-1 (+17.6%) (28.6 ± 1.1 mmol.l-1; p <0.001, CI = 6.0, 4.1, *d* =5.22) and SBC3 was 5.9 ± 1.1 mmol.l-1 (+20.0%) (29.5 ± 1.0 mmol.1-1; p <0.001, CI = 6.9, 5.0, *d* =6.58) greater than PLA (23.6 ± 0.7 mmol.l-1). There was no difference between SBC2 and SBC3 (p =0.34, CI = -2.3, 0.6, *d* =0.82).

Post exercise HCO3- was +1.8 ± 1.3 mmol.l-1 (+12.3%) greater for SBC2 (16.0 ± 2.2 mmol.l-1; p =0.004, CI = 2.9, 0.6, *d* =0.79), and +1.5 ± 1.3 mmol.l-1 (+10.9%) greater for SBC3 (15.8 ± 2.7 mmol.l-1; p =0.01, CI = 2.7, 0.4, *d* =0.62) compared to PLA (14.2 ± 2.2 mmol.l-1). There was a main effect for treatment in HCO3- change during exercise (p <0.001, *P*η2 =0.714), whereby the change in HCO3- was 3.3 ± 1.8 mmol.l-1 (+25.9%) greater following SBC2 (12.7 ± 2.6 mmol.l-1; p =0.001, CI = 4.9, 1.6, *d* =1.37) and 4.4 ± 1.7 mmol.l-1 (+31.7%) greater for SBC3 (13.8 ± 2.7 mmol.l-1; p <0.001, CI = 5.9, 2.8, *d* =1.78) compared to PLA (9.4 ± 2.0 mmol.l-1). There was no difference between SBC conditions (p =0.59, CI = -1.2, 3.3; *d* =0.40). A main effect for time was observed for BLa (p <0.001, *P*η2 =0.957) with all conditions displaying greater post-exercise BLa compared to pre-exercise (Figure 4c). Post-exercise, a time × treatment interaction was observed for BLa (p <0.001, *P*η2 =0.577) as SBC2 was +3.7 ± 2.8 mmol.l-1 (+22.5%) greater than PLA (16.1 ± 3.4 vs. 12.5 ± 2.7 mmol.l-1, p =0.006, CI = 1.1, 5.8, *d* =1.13; Figure 4c), with SBC3 greater by +3.7 ± 2.4 mmol.l-1 (+22.7%) (16.1 ± 3.4 mmol.l-1; p =0.002, CI = 1.5, 5.8, *d* =1.13). No differences between SBC conditions were evident for post-exercise BLa (p =0.61, CI = -2.3, 2.2; *d* =0.01).

\*Figure 4 near here\*\*

***Gastrointestinal (GI) discomfort***

Four participants reported symptoms of belching and stomach bloating in SBC2, compared to seven participants reporting symptoms of belching, stomach cramp, bowel urgency and diarrhoea in SBC3. There was no significant difference in severity of GI discomfort between SBC treatments (SBC2 =1.4 ± 1.5 vs. SBC3 =4.6 ± 3.6; p =0.10), although a large effect size was evident (*d =*0.88). Similarly, time to peak GI discomfort was not significantly different between SBC treatments (SBC2 =20 ± 24 vs. SBC =43 ± 31min, p =0.13), although revealed a large effect size (*d*  =0.80).

***Heart rate (HR), ratings of perceived exertion (RPE) and affective perceptions of work rate scale***

Heart rate was unaffected by NaHCO3 ingestion as no time × treatment interaction was observed (p =0.56, *P*η2 =0.055). There was a main effect for time (p <0.001, *P*η2 =0.977) for HR and mean data combined from all treatments displayed HR at 500m was 144 ± 3 b.min-1, compared to 171 ± 2b.min-1 at 4 km, respectively. A main effect for time was observed for RPEO (p <0.001, *P*η2 =0.849), as at 1 km RPEO was 14 ± 1 compared to 17 ± 1 at 4 km, although no time × treatment was apparent (p =0.31, *P*η2 =0.109). A main effect for time was observed for RPEL (p <0.001, *P*η2 =0.657), as at 1 km RPEL was 15 ± 1 compared to 18 ± 0 at 4 km, although no time × treatment interaction was evident (p =0.73, *P*η2 =0.085). Affective perceptions of work rate revealed no time × treatment interaction (p =0.38, *P*η2 =0.099) or main effect for time (p =0.92, *P*η2 =0.020).

**Discussion**

In agreement with our hypothesis, this study reports that both 0.2 g.kg-1 (SBC2) and 0.3 g.kg-1 BM (SBC3) NaHCO3 improves 4 km TT cycling performance in trained cyclists when individualised to a predetermined time to peak HCO3-. Time to complete the time trial was 2.2% faster in SBC2 and 2.3% in SBC3 compared to PLA, whilst there was also no statistical difference between SBC conditions suggesting both amounts are appropriate to enhance this type of exercise performance. Combining such performance effects with the reduced instances and severity of GI discomfort following 0.2 g.kg-1 BM NaHCO3 however, the present study findings suggest this amount may be more attractive to the athlete in a practical setting.

The findings of the present study contrast that of two recent studies reporting no effect of NaHCO3 on 4 km TT performance (Callahan et al., 2017; Correia-Oliveira et al., 2017). Indeed, Callahan et al. (2017) reported a ‘*possibly trivial*’ effect and Correia-Oliveira (2017) reported no significant supplement interaction in ANOVA analysis following 0.3 g.kg-1 BM NaHCO3. In comparison, the present study displayed a statistically significant effect and a moderate effect size for both SBC2 and SBC3. This ergogenic effect was most likely realised due to supplementing NaHCO3 to a predetermined time to peak HCO3-, as this would have ensured peak bioavailability of HCO3- at the commencement of exercise. In particular, the increase in HCO3- following the SBC2 treatment of the present study was similar, whilst the SBC3 treatment was superior, to the values reported in the aforementioned studies with 0.3 g.kg-1 BM NaHCO3 (SBC2 = 4.9 to 5.5 mmol.l-1, SBC3 = 5.6 to 6.5 mmol.l-1 vs. Callaghan et al. = +3 mmol.l-1 vs. Correia-Oliveira et al. = +5mmol.l-1). Based on this evidence, it is therefore more appropriate to identify time to peak HCO3- prior to the use in exercise to elicit ergogenic effects on performance. A consideration, however, is that identifying time to peak HCO3- presents a logistical challenge, as this would require a visit to a laboratory or access to a portable blood gas analyser.

A unique finding of the present study was the lack of a dose-dependent effect on exercise performance, with SBC3 improving performance to a similar magnitude as SBC2. These findings are in contrast to McNaughton (1992), reporting 0.3 g.kg-1 BM NaHCO3 improved TWD greater than 0.2 g.kg-1 BM NaHCO3 during 60 seconds of maximal cycling compared to a placebo. The negligible 0.1% difference observed between SBC2 and SBC3 are more in agreement with the findings of McKenzie et al. (1986) reporting a 0.3% difference between 0.15 g.kg-1 BM and 0.3 g.kg-1 BM NaHCO3. Individual performance responses did reveal that three participants improved to a greater extent in SBC2 compared to SBC3, whilst two participants improved to a greater extent in SBC3 compared to SBC2 based on the 3 s cut off from the prior power calculation. These data combined suggest lower amounts of NaHCO3 (i.e. 0.2 g.kg-1 BM) are likely to be sufficient to enhance exercise of this duration and intensity, although athletes should trial each dose prior to use in competition to evaluate which amount of NaHCO3 provides a larger ergogenic benefit. Likewise, considering the potential for the onset of GI discomfort, athletes who are susceptible to such symptoms should conduct a risk:benefit analysis of NaHCO3 supplementation.

It is purported that mitigating the severity of GI discomfort is important to obtain a performance benefit following NaHCO3 supplementation, as Saunders et al. (2014) reported a significant effect on performance only upon the removal of participants who suffered from GI discomfort. The present study findings contrast this by reporting a significant 2.3% improvement following both SBC2 and SBC3, despite the occurrence of mild to moderate GI discomfort. Reasons for this may be due to the good tolerance of NaHCO3 in our participant cohort, although it is difficult to compare with the work of Saunders et al. (2014) as no explicit statistical analysis on GI discomfort is available. Nonetheless, there may still be a relationship between GI discomfort and performance, as for instance, participant 8 in the present study suffered from moderate diarrhoea and bowel urgency in SBC3 and no improvement in performance was observed (0.1 s). While performance in SBC2 was improved by 8.9 s in the same participant when no instances of GI discomfort occurred. Combining this finding with other investigations where participants have self-withdrawn, or have been withdrawn by the research team due to the severity of GI discomfort, the responses from NaHCO3 still warrant observation in training prior to use in competition (Gough et al., 2017a, 2017b; Jones et al., 2016). Nonetheless, smaller amounts of NaHCO3 may be an attractive solution to the athlete to reduce the severity of GI discomfort symptoms whilst still providing ergogenic effects to exercise performance.

The enhancements of acid base balance following NaHCO3 are the most likely mechanism for an improved performance in the present study, as both SBC2 and SBC3 raised HCO3- and pH significantly compared PLA. An increase in extracellular HCO3- is suggested to increase H+ efflux during exercise due to the up-regulation of the lactate/H+ cotransporter, leading to increased provision of anaerobic energy contribution (Marx et al., 2002). The change in HCO3- was superior in both SBC2 (+25.9% vs. PLA) and SBC3 (+31.7% vs. PLA) whilst post-exercise blood lactate was also significantly higher (~15%) in the SBC conditions. These changes in blood acid base balance and BLa are indicative of exercise at higher exercise intensities in the SBC conditions and hence, improved performance. Furthermore, between SBC conditions there were minimal differences in respect of blood metabolites changes prior to, or during exercise. This provides an explanation why there were no dose-dependent effects on performance in the present study.

**Conclusion**

Ingestion of NaHCO3 individualised to time to peak HCO3- improves 4 km TT cycling performance in trained cyclists. Ingestion of both 0.2 g.kg-1 BM and 0.3 g.kg-1 BM NaHCO3 equally increase buffering capacity and subsequently provided ergogenic benefits to exercise performance. No difference was observed between SBC conditions; therefore, athletes can plausibly use a lower amount of NaHCO3 (i.e. 0.2 g.kg-1 BM) particularly if they are susceptible to the onset GI discomfort. Future research should investigate the dose-dependent effects of both 0.2 g.kg-1 BM and 0.3 g.kg-1 BM NaHCO3 during exercise of different intensities and durations.

**Disclosure statement**

The authors report no conflicts of interest.

**References**

1. Allen, D. G., Lamb, G. D., & Westerblad, H. (2008). Skeletal Muscle Fatigue: Cellular Mechanisms. *Physiological Reviews*, 88(1), 287–332.
2. Astorino TC. (2012). Reliability and Validity of the Velotron Racermate Cycle Ergometer to Measure Anaerobic Power. *International Journal of Sports Medicine*, 32(32), 1–5.
3. 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), 807–13.
4. Borg, G. A. (1982). Psychophysical bases of perceived exertion. *Medicine and Science in Sports and Exercise,* 14(5), 377–81.
5. Callahan, M. J., Parr, E. B., Hawley, J. A., & Burke, L. M. (2017). Single and Combined Effects of Beetroot Crystals and Sodium Bicarbonate on 4-km Cycling Time Trial Performance. *International Journal of Sports Nutrition and Exercise Metabolism,* 27(3), 271–278.
6. Carr, A. J., Hopkins, W. G., & Gore, C. J. (2011). Effects of acute alkalosis and acidosis on performance: a meta-analysis. *Sports Med (Auckland, N.Z.)*. 2011; 41(10): 801–14.
7. Christensen, P. M., Shirai, Y., Ritz, C., & Nordsborg, N. B. (2017). Caffeine and bicarbonate for speed. A meta-analysis of legal supplements potential for improving intense endurance exercise performance. *Frontiers in Physiology,* 8, 240.
8. Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences*. 2nd ed. Lawrence Erlbaum Associates, 567 p.
9. Correia-Oliveira, C. R., Lopes-Silva, J. P., Bertuzzi, R., McConell, G. K., Bishop, D. J., Lima-Silva, A. E., & Kiss, M.A.P.D. (2017). Acidosis, but not alkalosis, affects anaerobic metabolism and performance in a 4-km time trial. *Medicine and Science and Sports and Exercise.* [Epud ahead of print]
10. Costa, V. P., Guglielmo, L.G.A., & Paton, C. D. (2017). Validity and reliability of the PowerCal device for estimating power output during cycling time trials. *Journal of Strength and Condition Research,* 31(1), 227-232.
11. Deb, A. 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.* 2017; [Epub ahead of print].
12. 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), 111–22.
13. Fitts, R. H. (2008). The cross-bridge cycle and skeletal muscle fatigue. *Journal of Applied Physiology*, 104(2), 551-8*.*
14. Fitts, R. H. (2016). The role of acidosis in fatigue. *Medicine and Science in Sports & Exercise*, 48(11), 2335-2338.
15. Gastin, P. B. (2001). Energy system interaction and relative contribution during maximal exercise. *Sports Medicine*, 31(10), 725-41.
16. Gough, L. A., Deb, S. K., Sparks, S. A., & McNaughton, L. R. (2017a). The Reproducibility of Blood Acid Base Responses in Male Collegiate Athletes Following Individualised Doses of Sodium Bicarbonate: A Randomised Controlled Crossover Study. *Sports Medicine*. [Epub ahead of print].
17. Gough, L. A., Rimmer, S., Osler, C.J., & Higgins, M. F. (2017b). Ingestion of sodium bicarbonate (NaHCO3) following a fatiguing bout of exercise accelerates post-exercise acid-base balance recovery and improves subsequent high-intensity cycling time to exhaustion. *International Journal of Sports Nutrition and Exercise Metabolism,* [Epub ahead of print].
18. Gough, L. A., Deb, S.K., Sparks, A & McNaughton, L.R. (2017c) The reproducibility of 4-km time trial (TT) performance following individualised sodium bicarbonate supplementation: a randomised controlled trial in trained cyclists. *Sport Medicine - Open*, 3(1), 34.
19. 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 Sports Nutrition and Exercise Metabolism,* 26(5), 445–453.
20. Lakens, D. (2013). Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs. *Frontiers in Physiology,* 4(863), 1-12.
21. 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. *Europen Journal of Applied Physiology*, 87(1), 72–77.
22. Matson, L. G., & Tran, Z. V. (1993). Effects of sodium bicarbonate on anaerobic performance: a meta-analytic review. *International Journal of Sports Nutrition and Exercise Metabolism*, 3(1), 2-28.
23. McKenzie, D. C., Coutts, K. D., Stirling, D. R., Hoeben, H. H., & Kuzara, G. (1986). Maximal work production following two levels of artificially induced metabolic alkalosis. *Journal of Sports Sciences*, 4(1), 35–38.
24. McNamara. J., & Worthley, L. I. (2001). Acid-base balance: part II. Pathophysiology. *Critical Care and Resuscitation,* 3(3), 188–201.
25. McNaughton, L. R. (1992). Bicarbonate ingestion: effects of dosage on 60 s cycle ergometry. *Journal of Sports Science,* 10(5), 415–23.
26. 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): 233–44.
27. 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. *Journal of Strength of Conditioning Research,* 30(2), 561–568.
28. Nakagawa, S., & Cuthill, I.C. (2007). Effect size, confidence interval and statistical significance: a practical guide for biologists. *Biological Reviews of the Cambridge Philosophical Society,* 82(4), 591-605.
29. Peart, D.J., Siegler, J.C., & Vince, R.V. (2012). Practical recommendations for coaches and athletes: a meta-analysis of sodium bicarbonate use for athletic performance. *Journal of Strength and Conditioning Research,* 26(7), 1975-83.
30. Price, M.J., & Singh, M. (2008). Time course of blood bicarbonate and pH three hours after sodium bicarbonate ingestion. *International Journal of Sports, Physiology and Performance,* 3, 240-242.
31. Reilly, T. (1990). Human circadian rhythms and exercise. *Critical Reviews in Biomedical Engineering,* 18(3), 165-80.
32. Siegler, J. C., Midgley, A. W., Polman, R.C.J., & Lever, R. (2009). Effects of various sodium bicarbonate loading protocols on the time-dependent extracellular buffering profile. *Journal of Strength and Conditioning Research,* 0(0), 1-7.
33. Stone, M. R., Thomas, K., Wilkinson, M., St Clair Gibson, A., & Thompson, K. G. (2011). The 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.
34. Thomas, K., Goodall, S., Stone, M., Howatson, G., St Clair Gibson, A., & Ansley, L. (2015). Central and peripheral fatigue in male cyclists after 4-, 20-, and 40-km time trials. *Medicine and Science in Sports and Exercise*, 47(3), 537–46.
35. Westerblad, H., Allen, D. G., & Lännergren, J. (2002). Muscle fatigue: lactic acid or inorganic phosphate the major cause? *News in Physiological Sciences*, 17, 17-21.

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Figure 1 – Mean (±SD), and individual 4 km time trial performance times following each condition. \*denotes significantly different from PLA (p <0.05).

Figure 2 – Mean (±SD) cycling power (A) and speed (B) during each 0.5 km segment of the time trial. Significant increase (p <0.05) in SBC2 = # and SBC3 = ## compared to PLA.

Figure 3 – Individual time to peak blood bicarbonate (HCO3-) following SBC2 and SBC3.

Figure 4 – Mean (±SD) blood pH (A), bicarbonate (HCO3-) (B) and lactate (C) responses during experimental treatments. Significantly different (p <0.05) in SBC2 = # and SBC3 = \* compared to PLA.