Journal of Science and Medicine in Sport 24 (2021) 301–306

Contents lists available at ScienceDirect

Journal of Science and Medicine in Sport

journal homepage: www.elsevier.com/locate/jsams

Original research

Sodium bicarbonate improves sprint performance in endurance cycling

Sebastiaan Dalle[a], Katrien Koppo[a], Peter Hespel[a,b,*]

[a] Exercise Physiology Research Group, Department of Movement Sciences, KU Leuven, Belgium
[b] Bakala Academy Athletic Performance Center, KU Leuven, Belgium

ARTICLE INFO

Article history:
Received 31 January 2020
Received in revised form 14 August 2020
Accepted 12 September 2020
Available online 25 September 2020

Keywords:
Acid–base balance
Exercise performance
Supplementation
$NaHCO_3$
Cycling
Athletes

ABSTRACT

Objectives: Oral sodium bicarbonate intake ($NaHCO_3$) may improve performance in short maximal exercise by inducing metabolic alkalosis. However, it remains unknown whether $NaHCO_3$ also enhances all-out performance at the end of an endurance competition. Therefore, the present study investigated the effect of stacked $NaHCO_3$ loading on sprint performance following a 3-h simulated cycling race.
Design: Double-blind randomized placebo-controlled cross-over study.
Methods: Eleven trained male cyclists (22.3 (18.3–25.3) year; 73.0 (61.5–88) kg; VO_2max: 63.7 (57–72) ml kg^{-1} min^{-1}) ingested either 300 mg kg^{-1} body weight $NaHCO_3$ (BIC) or NaCl (PL). $NaHCO_3$ or NaCl was supplemented prior to (150 mg kg^{-1}) and during (150 mg kg^{-1}) a 3-h simulated cycling race with a 90-s all-out sprint (90S) at the end. Capillary blood samples were collected for determination of blood pH, lactate and HCO_3^- concentrations. Analysis of variance (lactate, pH, HCO_3^-) and paired t-test (power) were applied to compare variables across condition (and time).
Results: $NaHCO_3$ intake improved mean power during 90S by ~3% (541 ± 59 W *vs.* 524 ± 57 W in PL, $p = 0.047$, Cohen's D = 0.28, medium). Peak blood lactate concentration and heart rate at the end of 90S were higher ($p < 0.05$) in BIC (16.2 ± 4.1 mmol l^1, 184 ± 7 bpm) than in PL (12.4 ± 4.2 mmol l^{-1}, 181 ± 5 bpm). $NaHCO_3$ ingestion increased blood [HCO_3^-] (31.5 ± 1.3 *vs.* 24.4 ± 1.5 mmol l^{-1} in PL, $p < 0.001$) and blood pH (7.50 ± 0.01 *vs.* 7.41 ± 0.03 in PL, $p < 0.05$) prior to 90S.
Conclusions: $NaHCO_3$ supplementation prior and during endurance exercise improves short all-out exercise performance at the end of the event. Therefore, sodium bicarbonate intake can be applied as a strategy to increase success rate in endurance competitions.

Practical implications

- For the first time, it is shown that sodium bicarbonate loading prior to and during a simulated cycling race improves a 90-sec all-out sprint at the end of the race.
- Stacked sodium bicarbonate loading of 0.3 g/kg body mass prior to and during cycling does not elicit gastrointestinal disturbances.
- Coaches and athletes should test the supplementation protocol on training sessions before its application in competition.

1. Introduction

Success in prolonged endurance events such as road cycling, triathlon, long-distance running or cross-country skiing, often depends on the capacity to outperform residual competitors by short all-out exercise in the final stage of the race.[1] This requires aerobic endurance training to be combined with specific training to develop anaerobic power and capacity. The crucial role of late stage high power production to achieve success in endurance races justifies the use of nutritional interventions to enhance anaerobic capacity.

The spectrum of nutritional interventions to beneficially impact short all-out performance is narrow. It was previously demonstrated that oral creatine and β-alanine supplementation can improve sprint performance at the end of prolonged exercise.[2,3] However, probably the most popular nutritional supplement to improve anaerobic performance is sodium bicarbonate loading.[4,5] Although it is still a matter of debate,[6] the prevailing opinion is that intramyocellular proton (H^+) accumulation plays an important role in the development of muscle fatigue during high-intensity muscle contractions.[7] Therefore, any intervention that may suppress intramyocellular H^+ accumulation could con-

* Corresponding author.
E-mail address: peter.hespel@kuleuven.be (P. Hespel).

https://doi.org/10.1016/j.jsams.2020.09.011

tribute to alleviate muscular fatigue.[7,8] There is ample evidence to indicate that $NaHCO_3$ intake prior to exercise, by increasing extracellular buffer capacity, facilitates H^+ as well as $lactate^-$ ion efflux from muscles,[9,10] which eventually may result in improved performance.[11–14]

However, findings with regard to the ergogenic effect of $NaHCO_3$ loading in short maximal exercise are equivocal. This is at least partly explained by different reliability and duration ($\leq$1 min[15] *vs.* >5 min[16]) of the maximal exercise protocols used, as well as duration (single dose[17–19] *vs.* stacked dose[11] *vs.* multiple day loading[20,21]) and dosage ($\leq$3 mg kg^{-1} BM[22] *vs.* >3 mg kg^{-1} BM[11]) of the $NaHCO_3$ supplementation. In addition, responses to $NaHCO_3$ loading are highly variable between individuals,[23] also with regard to the incidence of gastrointestinal distress that may acutely impair performance.[15,24] The high incidence of GI problems, which as a rule is most prominent about 1–2 h after high-dose sodium bicarbonate intake,[25] has also prevented $NaHCO_3$ loading to be considered as a feasible procedure to enhance anaerobic capacity.[26] Surprisingly, it has never been investigated whether $NaHCO_3$ intake during very prolonged endurance exercise can increase the HCO_3^- concentration to a sufficient degree to improve all-out performance in the final stage of the event. It was recently demonstrated that stacked $NaHCO_3$ ingestion throughout the day, resulting in 400 mg kg^{-1} BW $NaHCO_3$ intake over a 9-h period, significantly improved power output in a 2-min all-out exercise at the end of the loading period.[11] In addition, this ergogenic effect appeared in total absence of any GI discomfort.[11]

The present study investigated whether stacked sodium bicarbonate loading in the hours before and during a prolonged endurance exercise bout, can result in a higher HCO_3^- concentration by the time high anaerobic capacity is needed to be successful in a final all-out exercise bout or sprint. The authors hypothesize that stacked $NaHCO_3$ loading by increasing extracellular buffer capacity can improve performance in a short all-out exercise bout at the end of a 3-h simulated cycling race.

2. Methods

Eleven male cyclists (age: 22.3(18.3–25.3) year; height: 1.83(1.67–1.95) m; weight: 73.0(61.5–88.0) kg; VO_2max: 63.7(57.0–72.0) ml kg^{-1}·min^{-1}) who participated in regional competitions, volunteered to participate in the study. They were informed in detail on the aim and the procedures of the study protocol and signed a written informed consent as approved by the Ethics Committee Research at UZ/KU Leuven. All participants were non-smokers, abstained from dietary supplements for at least 3 months prior to the start of the study, and had a maximal oxygen uptake rate (VO_2max) of at least 55 ml kg^{-1}·min^{-1}. Furthermore, participants were physically screened for contraindications to participate in maximal exercise. One week prior to the first experimental session an incremental cycling test was performed to determine the participant's lactate threshold (LT) and VO_2max. Initial workload was 60 W and was increased by 40 W per 8-min until volitional exhaustion (332 ± 42 W). Capillary blood was sampled from an earlobe at 4-min intervals throughout the test. LT (294 ± 42 W) was defined as the intensity at which blood lactate increased by 1 mmol·l^{-1} from min 4 to 8 within a given 8-min workload step. Following the incremental cycling test, the participants performed a cool down by cycling at 100 W for 15 min. Thereafter they performed a 90-s all-out isokinetic cycling bout as a familiarization for the same test to be performed in the later experimental sessions. Based on the results from the incremental cycling test (VO_2max and peak power output) the participants were classified into performance level 1–5 according to De Pauw et al.[27] Three participants were ranked at level 3 ('trained', 'competitive'), six at level 4 ('highly trained', 'national cycling league') and two participants at level 5 ('professional cyclists').

The double-blinded, placebo-controlled, randomized crossover study involved two experimental sessions ($NaHCO_3$, BIC *vs.* placebo, PL supplementation) with a 1-week washout period in between. Treatment allocation was done by coin flipping by a local investigator who was otherwise not involved in the study, and assuring half of the participants to start with BIC *vs.* the others half with PL. All exercise testing was undertaken in an air-conditioned laboratory (18 °C and 60% relative humidity). During the experiments, the cycling ergometers were positioned in front of the cooling units, which were set at maximal airflow rate to obtain optimal cooling of participants during the exercise protocol. Participants were asked to abstain from strenuous exercise for at least 48 h prior to each session. All exercise testing was done on the participants' personal race bicycle being mounted on an electromagnetically braked cycle ergometer (Avantronic® Cyclus 2, Leipzig, Germany) calibrated prior to the experiments.

The evening before the experimental sessions, participants received a standardized dinner (1200 kcal; 201 g CHO; 48 g protein; 22 g fat). After dinner they remained fasted until reporting to the laboratory next morning, yet were allowed to drink water at libitum. Upon arrival, they received a carbohydrate-rich breakfast (880 kcal; 154 g CHO; 32 g protein; 15 g fat), together with 90 mg kg^{-1} BW $NaHCO_3$ or appearance-matched placebo delivering equimolar amounts of sodium. Forty-five and 90 min after breakfast two more doses of 30 mg kg^{-1} BW $NaHCO_3$ were ingested. These supplements were administered in the form of 700 mg, the number of which was adjusted to match the prescribed dose kg^{-1} BW as close as possible. Two hours after breakfast the participants started a 3-h intermittent exercise bout (see below), during which they received 50 mg kg^{-1} BW $NaHCO_3$ (#1370131000 Merck Millipore, Massachusetts, USA) per hour dissolved in 500 mL of a 6% maltodextrine (Body & Fit, Heerenveen, The Netherlands) solution, or taste and color-matched placebo (NaCl, #1064060500 Merck Millipore, Massachusetts, USA). In addition the participants received an energy bar containing 30 g of carbohydrates (6d Sports Nutrition, Oudenaarde, Belgium) in order to obtain a total oral carbohydrate intake at a rate of 60 g per hour. In total, from 2 h prior to the start until the end of the 3-h exercise bout, the participants ingested 300 mg kg^{-1} BW $NaHCO_3$.

The exercise protocol included a 3-h intermittent exercise bout aimed to simulate a cycling race (RACE),[3] followed by a 90-s all-out 'sprint' (90S). All exercise was performed with the personal race bike of the participant mounted on calibrated cycling ergometers (Avantronic® Cyclus 2, Leipzig, Germany). To allow simultaneous participation of different subjects in the experiments, different ergometers were used for RACE, yet to avoid slight calibration differences between devices, the same ergometer was used for both experimental conditions in every participant. Conversely, all 90S tests were done on one single ergometer which was put into the isokinetic operation mode with cadence fixed at 100 rpm, and which was calibrated immediately prior to the experiments. RACE consisted of six consecutive 30-min blocks during which exercise intensity was varied per 5-min intervals between 60 and 90% of LT taken from the preliminary testing. Cadence during RACE was fixed at 85–95 rpm. Hereafter the participant's race bike was moved to the isokinetic sprint ergometer while the participant rested for 2–3 min. Initial workload for 90S was set at 5 N kg^{-1} BW (330 ± 40 N) and no verbal encouragement was given during the test. Feedback was limited to the 90-s time countdown.

Capillary blood samples were collected from a hyperaemic earlobe into heparinized glass capillaries (70-μL; Clinitubes, Radiometer Medical ApS, Copenhagen, Denmark). Samples were taken prior to the supplementation, at the start, in the middle and at the end of RACE, and 3 min post 90S, and were immediately mixed

for 15 s. Samples were then immediately analyzed for blood HCO_3^- content, blood pCO_2 and pH using an automated acid–base laboratory (ABL90 Flex, Radiometer Medical ApS, Copenhagen, Denmark) and also blood lactate concentration was determined (Lactate Pro 2, Arkray, Japan). Heart rate (Polar, Kempele, Finland) and power output (Avantronic® Cyclus 2, Leipzig, Germany) were continuously measured during exercise. Heart rate data of one participant were lost due to technical issues. The fatigue index (%) was calculated as the [peak power – final power (last 10-s)]/peak power × 100. Rating of perceived exertion (RPE) was assessed immediately after RACE and following 90S by scoring a 15-point Borg-scale.[28] Gastrointestinal (GI) distress was assessed prior to the intervention and immediately after 90S through a standardized questionnaire[29] with 12 questions addressing GI discomfort at systemic, upper-abdominal and lower-abdominal level on a 9-point scale.

All data are presented as means ± SD, or mean and range in parentheses. The mean power output (MPO) of 90S was calculated per 10-s intervals as well as for the full exercise bout. The variables MPO, maximal PO, maximal blood lactate concentration, maximal heart rate, blood pH and fatigue index were normally distributed on all time points in both conditions (Kolmogorov–Smirnov test of normality; $p > 0.05$). Blood HCO_3^- was not normally distributed at the first time point in PL (Kolmogorov–Smirnov $p = 0.036$), but was normally distributed on the other four time points. Normally distributed data (and blood HCO_3^-) were analyzed with appropriate parametric statistical tests. Conditions were compared by repeated measures ANOVA across treatments (PL *vs.* BIC) and time, using Bonferroni post-hoc tests for multiple comparisons whenever a significant treatment × time interaction was found. The effect of BIC *vs.* PL on mean and peak power outputs, fatigue index, peak heart rate, and blood lactate concentration during 90S was evaluated by two-sided paired Student's t-test. Delta (Δ) (±SD) values are provided to address the difference between BIC and PL (at a given time point). GI distress and RPE data were non-normally distributed (Kolmogorov–Smirnov $p < 0.05$) and were analyzed with the nonparametric Wilcoxon Signed Rank test to compare BIC *vs.* PL. Where relevant, Cohen's D (D) was calculated as index of effect size (ES) for the t-tests (0.2 = small, 0.5 = medium, >0.8 = large), and eta-squared (η^2) was used as index of ES for ANOVA (0.02 = small, 0.13 = medium, 0.26 = large). The ES of nonparametric data (GI, RPE) was calculated as $r = z/\sqrt{N}$ (0.1–0.3 = small, 0.3–0.5 = medium, >0.5 = large).[30] Significance was accepted for $p < 0.05$. All statistical analyses were performed using SPSS version 20 (IBM, Chicago, USA).

3. Results

Effect of bicarbonate intake on performance in 90S (Figs. 1B, 2) – During 90S power output peaked after ~2.5 s, where after it gradually decreased until the end of the exercise bout. Peak power outputs were similar between the groups (PL: 864 ± 169; BIC: 853 ± 150 W; Δ11 ± 157 W; $t = 0.238$; $df = 10$; $p = 0.817$). But MPO over the full 90-sec bout was ~3% higher in BIC (541 ± 59 W) than in PL (524 ± 57 W; Δ17 ± 25 W; $t = -2.270$; $df = 10$; $p = 0.047$; $D = 0.29$) (Fig. 2A). Eight out of 11 participants increased their MPO during BIC, with a 95% confidence interval at 0.3–33.7 W. Fatigue index was similar between conditions (−49.3 ± 11.7%; Δ1.7 ± 35.3 %; $t = 0.310$; $df = 10$; $p = 0.763$) though. RPE at the end of 90S was similar between PL (18.5 ± 1.3) and BIC (18.4 ± 1.2; $z = -0.272$; $p = 0.785$). Nonetheless, compared with PL (181 ± 5 bpm) peak heart rate elicited by 90S was higher in BIC (184 ± 7 bpm; Δ3.1 ± 2.6 bpm; $t = -3.832$; $df = 9$; $p = 0.004$; $D = 0.52$) (Fig. 1B).

Workload and fatigue during RACE – Total work done during RACE was 2266 (1587–2825) kJ. Workloads at 60, 70, 80 and 90% of LT were 176 (123–219), 205 (144–256), 234 (164–292) and 264 (185–329) W, respectively. These workloads corresponded to 74 (69–79), 76 (71–82), 81 (76–85) and 83 (79–88.1) % of peak heart rate taken from the VO_2max test. Heart rates during RACE were similar between the experimental conditions at any time ($F = 0.617$; $df = 4$; $p_{interaction} = 0.66$; $F = 0.839$; $df = 1$; $p_{condition} = 0.373$). Blood lactate concentration values at 60% of LT were also similar at ~1.2–1.4 mmol l^{-1} between conditions ($F = 0.096$; $df = 2$; $p_{interaction} = 0.91$; $F = 2.134$; $df = 1$; $p_{condition} = 0.16$). Accordingly, RPE at the end of RACE was 14.5 ± 1.2 in PL *versus* 13.8 ± 1.8 in BIC ($z = -1.065$; $p = 0.29$).

Effect of bicarbonate intake on blood-acid base balance (Fig. 3, Fig. 1A) – Compared with PL, $NaHCO_3$ intake from baseline until the end of RACE increased blood HCO_3^- concentration by ~30% ($F = 108$; $df = 4$; $p_{interaction} < 0.001$). Blood pH concomitantly increased by ~0.1 unit in BIC, whilst it was stable in PL ($F = 43.5$; $df = 4$; $p_{interaction} < 0.001$; $F = 47.8$; $df = 1$; $p_{condition} < 0.001$). Thus at the start of 90S blood HCO_3^- concentration was 24.4 mmol l^{-1} (22.7–27.1) in PL, and was higher (31.5 (29.6–34.0) mmol l^{-1}) in BIC (Δ7.2 ± 1.5 mmol l^{-1}; $F = 148.63$; $df = 1$; $p < 0.001$). Corresponding blood pH values were 7.41 (7.39–7.48) in PL *versus* 7.50 (7.49–7.52) in BIC (Δ0.09 ± 0.02; $F = 99.1$; $df = 1$; $p < 0.001$). During 90S blood bicarbonate levels dropped more in BIC (−15.4 ± 3.0 mmol l^{-1}) than in PL (−10.6 ± 2.5 mmol l^{-1}; $t = 8.529$; $df = 10$; $p < 0.001$). Nonetheless, compared with PL, post 90S blood bicarbonate level was still higher in BIC (Δ2.3 ± 2.1 mmol l^{-1}; $F = 5.8$; $df = 1$; $p = 0.025$). 90S decreased blood pH to the same degree in both groups, yet due to the higher pre-exercise value, blood pH post exercise remained higher in BIC than in PL (Δ0.07 ± 0.06; $F = 6.7$; $df = 1$; $p = 0.018$). The effect of $NaHCO_3$ on HCO_3^- and pH levels can be considered very large, as ES values (η^2) for both variables were ~0.5 (before RACE), 0.8 (during RACE) and 0.9 (before 90S). After 90S, the ES was less pronounced, yet still high ~0.24. Compared with PL (0.9 ± 0.1 mmol l^{-1}) blood lactate concentration at the start of 90S was slightly higher in BIC (1.1 ± 0.2 mmol l^{-1}; $F = 3.1$; $df = 1$; $p = 0.095$; $\eta^2 = 0.13$). 90S increased blood lactate concentration more in BIC (+15.2 ± 4.0 mmol l^{-1}) than in PL (+11.5 ± 4.2 mmol l^{-1}; $t = -4.142$; $df = 10$; $p = 0.002$; $D = 0.85$), resulting in 16.2 (8.7–21.5) mmol l^{-1} post exercise blood lactate concentration in BIC *vs.* 12.4 (4.5–18.1) mmol l^{-1} in PL ($F = 4.6$; $df = 1$; $p = 0.044$; $\eta^2 = 0.19$) (Fig. 1A). Prior to 90S, the arterial partial CO_2 pressure ($PaCO_2$) was higher in BIC (40.3 (36.0–42.7) mmHg) *vs.* PL (38.1 (35.4–40.5) mmHg; $F = 9.613$; $df = 1$; $p = 0.006$; $\eta^2 = 0.33$), whereas this was not the case at the end of 90S (BIC: 32.2 (27.4–39) mmHg; PL: 31.2 (26.6–35.3) mmHg; $F = 0.598$; $df = 1$; $p = 0.45$). Consequently, although not significant ($t = 1.9$; $df = 10$; $p = 0.09$), compared to PL (−6.9 ± 3.2 mmHg), BIC induced a larger decrease of $PaCO_2$ (ΔPaCO2) (−8.1 ± 3.5 mmHg; $D = 0.34$).

Gastrointestinal discomfort – GI symptoms were negligible. In the total group of participants, and on a possible maximal score of 96, GI scoring was 2.0 (0–11) at the start, increasing to 4.1 (0–14) by the end of the exercise protocol ($z = -2.388$; $p = 0.017$; $r = 0.51$). However, values were not different between PL and BIC before ($z = -1.4$; $p = 0.156$) or after ($z = -0.282$; $p = 0.778$) the cycling protocol.

4. Discussion

An extensive number of studies over the last decades has investigated the effects of sodium bicarbonate supplementation on performance in short all-out exercise (for review see[5,8]). In contrast, only a few studies have addressed the effects of $NaHCO_3$ in events lasting 30 min or longer.[31–39] Some reported a minor ergogenic action of $NaHCO_3$ on endurance performance,[31,33,36,37,39] whilst others reported no effect.[32,34,35,38] In addition, all aforementioned studies only considered $NaHCO_3$ loading prior to the start of exer-

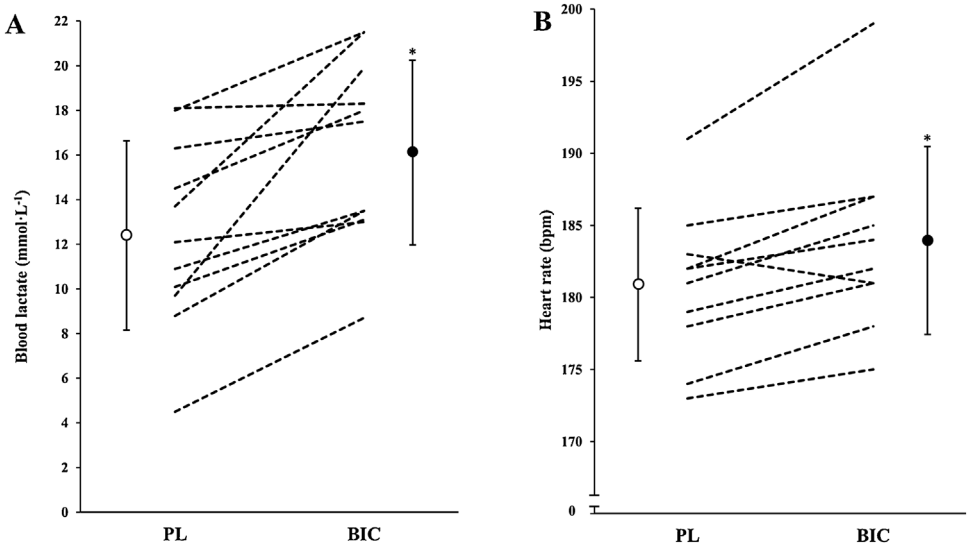

Fig. 1. Effect of sodium bicarbonate intake on blood lactate following and peak heart rate during a 90-s all out performance. Individual data points (n = 10–11) representing blood lactate (A) and peak heart rate (B). Participants first participated in a 3-h simulated cycling race. Immediately after, they performed a 90-sec all-out exercise bout. The participants received either oral sodium bicarbonate (BIC) or placebo (PL) supplements from baseline until the end of the 3-h cycling race. *P < 0.05 compared with PL.

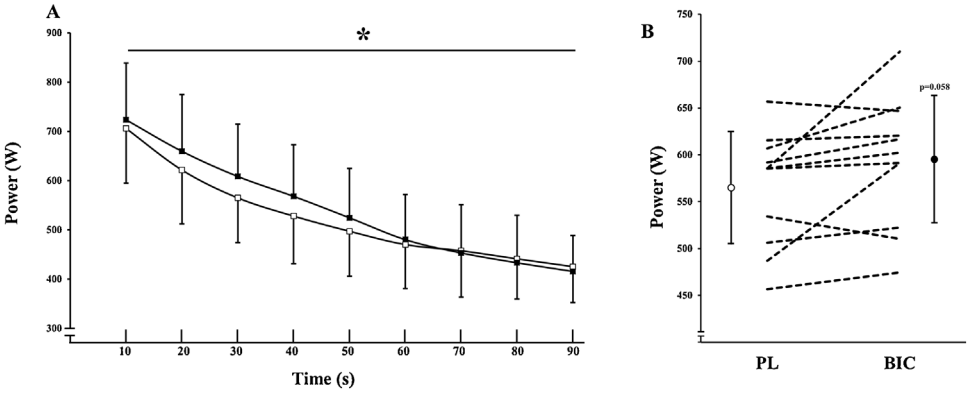

Fig. 2. Effects of sodium bicarbonate intake on 90-s all-out exercise performance at the end of a 3-h simulated cycling race. Participants participated in a 3-h simulated cycling race. Immediately after, they performed a 90-s all-out exercise bout (90S). Data (n = 11) represent the mean power output produced over the preceding 10-s time-interval (mean ± SD; A) and individual data points represent the mean power output during the first 60 s of 90S (B). The participants received either oral sodium bicarbonate (■; BIC) or placebo (□; PL) supplements from baseline until the end of the 3-h cycling race. *P < 0.05 compared with PL.

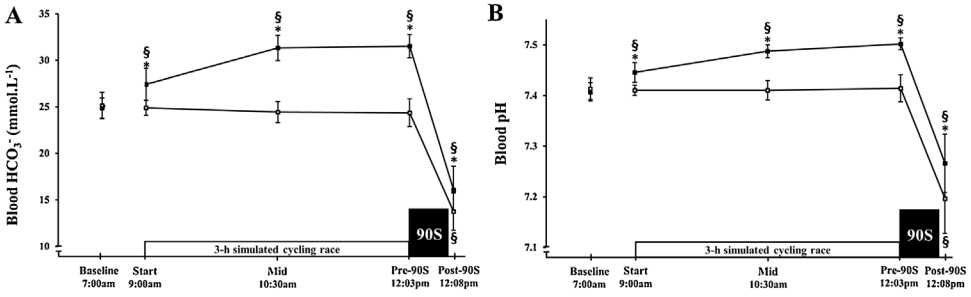

Fig. 3. Effects of sodium bicarbonate intake on blood acid-base balance. Data are mean ± SD (n = 11) for blood bicarbonate (HCO_3^-) (A) and blood pH (B) at baseline and at the start, middle, and end of a 3-h simulated cycling race, followed by a 90-s all-out exercise bout (90S). Participants received either oral sodium bicarbonate (■) or placebo (□) from baseline until the end of the 3-h race. *P < 0.05 compared with PL. §P < 0.05 compared with baseline.

cise, with exception of the study by Mitchell et al. in which $NaHCO_3$ or NaCl was infused intravenously during exercise.[35] However, the structure of a cycling race, which typically involves hours of mostly submaximal cycling preceding a high-intensity final phase, provides a window of opportunity to load sodium bicarbonate during the event in order to elevate blood HCO_3^- concentration in the approach of the final sprint. Furthermore, a stacked $NaHCO_3$ loading protocol in conjunction with intermittent exercise throughout the day can gradually raise blood bicarbonate in the absence of GI distress.[11]

Therefore, the present study evaluated a novel $NaHCO_3$ supplementation strategy aiming to enhance buffering capacity and thereby improving performance in short all-out exercise at the end of a prolonged endurance exercise event. The time schedule applied in our protocol is relevant for real life road cycling competitions, *i.e.* early morning breakfast followed by the start

of competition ~2 h later. Stacked $NaHCO_3$ loading from breakfast to the start of the event, delivering 150 mg kg^{-1} BW $NaHCO_3$ (9.2–13.2 g), raised blood bicarbonate levels by ~10%, resulting in a small initial increment in blood pH. Sustained $NaHCO_3$ loading at a rate of 50 mg kg^{-1} BW per hour during RACE increased blood HCO_3^- by an additional ~15%, resulting in ~27% higher blood HCO_3^- at the start of the final 90-s all-out exercise bout (90S). In the conditions of the current study, the rise in blood HCO_3^- amounted to 6.7 (5.8–7.7) mmol l^{-1} in BIC. Others reported slightly greater increments in blood HCO_3^-, *i.e.* by 8.2 (6.0–12.3) mmol l^{-1} upon ingestion of a 0.3 g kg^{-1} $NaHCO_3$ bolus.[40,41] These higher values might be due to the fact that HCO_3^- was measured every 10–15 min for 3 h after ingestion[40,41] whereas fewer measurements were done in the present study. Hence, we may have missed true peak blood HCO_3^- concentrations. Furthermore, in the present study, participants used some of the HCO_3^- load in H^+-buffering during RACE whilst they were resting in the study by Jones et al.[40] Blood pH at the start of 90S eventually increased by ~0.1 unit, reflecting a ~20% reduction in free extracellular proton concentration. This is in agreement with earlier studies showing a single 0.3 g kg^{-1} $NaHCO_3$ bolus to increase blood pH by ~0.1.[40] Importantly, this stacked $NaHCO_3$ loading procedure over the 5-h time-interval from breakfast to end of RACE was able to significantly increase the blood HCO_3^- concentration in the absence of any GI discomfort.

$NaHCO_3$ loading also resulted in a better performance in 90S at the end of the RACE. Compared with PL, MPO on average was ~3% higher in BIC. This magnitude of improved performance is in accordance with Bellinger et al.[18] and Driller et al.[17] Both studies concluded that acute $NaHCO_3$ loading (0.3 and 0.4 g kg^{-1}, respectively) improved MPO during a 4-min all-out sprint with ~3% in trained cyclists.[17,18] However, in untrained participants, $NaHCO_3$ supplementation was ineffective to improve similar all-out cycling performances.[19,42] McNaughton et al. suggested that more consistent ergogenic effects upon $NaHCO_3$ ingestion in trained individuals might be due to a better reliability of exercise performance, hence facilitating the detection of small but pertinent ergogenic effects.[5] The magnitude of the performance effect observed (~3%) was also greater than the coefficient of variation obtained by comparing performance between sessions 1 and 2 independent of the experimental conditions (1.47%), and indicating excellent reproducibility of the test procedure. In addition, eight of 11 participants exhibited a higher MPO during BIC than during PL, and confidence limits indicate 95% probability to experience a benefit in MPO ranging between 0.3 and 33.7 W. Furthermore, it is clear from Fig. 2A that this ergogenic effect was most prominent during the initial 60 s of 90S. In fact, when considering power outputs from 0 to 60 s, BIC stimulated power production in 9 out of the 11 participants ($t = -2.138$, $df = 10$; $p = 0.058$; $D = 0.46$; Fig. 2B). Interestingly, the increase in mean power output due to BIC (ΔMPO, calculated as MPO during BIC minus MPO during PL) was positively correlated with the greater drop in blood HCO_3^- ($r = 0.77$; $p = 0.006$) and with the increase in blood lactate concentration during 90S ($r = 0.608$; $p = 0.047$) in BIC compared with PL. This clearly indicates that the ergogenic effect generated by $NaHCO_3$ supplementation was at least partly, if not entirely, due to increased extracellular buffering capacity by higher blood HCO_3^- availability during 90S.

This improved performance in 90S conceivably was directly due to a higher rate of extracellular bicarbonate utilization. Decrease of the blood bicarbonate pool during 90S was ~50% greater in BIC (~15 mmol l^{-1}) than in PL (~10 mmol l^{-1}), which most likely reflects a higher efflux of both lactate ions and H^+ from the active muscles. Support for such mechanism comes from the observation that the peak blood lactate concentration during 90S was substantially higher in BIC (~16 mmol l^{-1}) than in PL (~12 mmol l^{-1}). Lactate export in muscle cells is effected by membrane-bound monocarboxylate transporters which operate as a lactate~H^+ cotransport system.[43] Decrease of extracellular H^+ concentration produced by high-dose HCO_3^- ingestion increases the outward gradient for H^+ across the sarcolemma, which in turn stimulates the simultaneous export of lactate and H^+ from muscle cells into the interstitial space. The ΔHCO_3^- in the present study was less pronounced than during a 4-min all-out sprint, during which blood HCO_3^- decreased with ~20 mmol l^{-1}, probably due to a longer time window during which HCO_3^- can be used.[17,18] Alternatively, due to limited blood HCO_3^- measurements, we may have missed true peak blood HCO_3^- concentrations, needed to calculate the total amount of HCO_3^- used during 90S. Between-subject variation in maximal blood lactate concentrations was relatively high (range: ~13 mmol l^{-1}). One subject reached a maximal blood lactate concentration of only 4.5 mmol l^{-1} in PL, conceivably due to low residual muscle glycogen content at the end of RACE. However, his response to $NaHCO_3$ (8.7 mmol l^{-1}; Δ + 4.2 mmol l^{-1}) is in line with the other participants (Δ + 3.8 ± 3.0 mmol l^{-1}). Furthermore, the low-end maximal blood lactate concentration was not associated with a low MPO, which was 73.5% higher than the power at his LT, similarly to the others, *i.e.* +88 ± 37%.

In agreement with earlier studies[11,19] blood pH drop during 90S was similar between BIC and PL. Blood pH depends on the ratio between [HCO_3^-] and pCO_2.[44] During 90S, ΔHCO_3^- was greater in BIC than in PL. Since ΔpH values were similar in both conditions, this suggests that ΔpCO_2 was higher in BIC. Indeed, compared to PL (−6.9 mmHg), the 90S-induced ΔpCO2 tended to be greater in BIC (−8.1 mmHg), which can (partly) be explained by the increased buffering of H^+ by HCO_3^-. It can be speculated that this would result in a higher VCO_2 during 90S.[45] However, this should be confirmed in future studies.

To our knowledge, this is the first study to report an increase in peak heart rate during short all-out exercise due to BIC. During exercise, metabolites such as H^+ accumulate in the working muscle and mainly stimulate the group IV afferents.[46] These eventually induce peripheral fatigue through regulation of the cardiovascular, hemodynamic and ventilatory responses to exercise, and prevent further metabolic disturbance by inhibition of neural output to muscles.[46] One might suggest that such inhibition is delayed due to prevention of premature muscular fatigue in BIC, which eventually allows greater cardiac sympathetic drive. There is also evidence indicating that acidosis blunts the sensitivity of cardiomyocytes to epinephrine,[47] which may also explain the higher peak exercise heart rate in BIC.[48] Furthermore, Linden & Norman proposed that acidosis (pH 6.95) stimulates vagal activity,[49] which might explain a lower peak heart rate in PL compared with BIC. However, the latter mechanism is less likely to be responsible for the observed differences since vagal suppression is rather engaged in the initial heart rate response to exercise,[50] whereas sympathic activity is responsible for further increases in heart rate during more strenuous exercise, as was the case in 90S.

To maximize the ecological validity of the study, especially with regard to the incidence of GI symptoms, dietary recommendations for race days were simulated, *i.e.* a CHO-rich meal ~2–3 h before RACE combined with consistent high-rate CHO intake during RACE (60 g per hour). In addition, combination of $NaHCO_3$ with a high-carbohydrate meal can facilitate the development of blood alkalosis as well as reduce the incidence of GI symptoms.[51]

In the current protocol the 3 h simulated cycling race consisted of mostly submaximal exercise bouts at workloads below the anaerobic threshold (60–90% of LT). However, in real competition the final sprint often is preceded by higher intensity exercise also involving repeated short all-out exercise bouts, or longer intervals at workloads exceeding the anaerobic threshold. Such exercises likely deplete the HCO_3^- concentration before the final sprint. Therefore, it remains to be established whether also under such

conditions the rate of $NaHCO_3$ used in the current protocol is able to maintain elevated buffering capacity until the final stage of the event.

5. Conclusion

This study evaluated the effect of stacked $NaHCO_3$ loading before and during a prolonged endurance exercise bout (~3 h) on all-out performance in the final stage of the event. Sodium bicarbonate loading delivering 300 mg kg^{-1} BW $NaHCO_3$ before and during the exercise gradually elevated blood HCO_3^-. This translated into improved power output in a 90-sec all-out exercise bout.

Acknowledgements

The authors would like to thank Monique Ramaekers for her skillful technical assistance during the experiments. The authors declare no financial support for the project.

References

1. Padilla S, Mujika I, Santisteban J et al. Exercise intensity and load during uphill cycling in professional 3-week races. *Eur J Appl Physiol* 2008; 102(4):431–438. http://dx.doi.org/10.1007/s00421-007-0602-9.
2. Vandebuerie F, Vanden Eynde B, Vanden EK et al. Effect of creatine loading on endurance capacity and sprint power in cyclists. *Int J Sport Med* 1998; 19:490–495.
3. Van Thienen R, Van Proeyen K, Vanden Eynde B et al. β-Alanine improves sprint performance in endurance cycling. *Med Sci Sports Exerc* 2009; 41(4):898–903. http://dx.doi.org/10.1249/MSS.0b013e31818db708.
4. Lancha Junior AH, de Salles Painelli V, Saunders B et al. Nutritional strategies to modulate intracellular and extracellular buffering capacity during high-intensity exercise. *Sport Med* 2015; 45:71–81. http://dx.doi.org/10.1007/s40279-015-0397-5.
5. Mcnaughton L, Deb S, Sparks A et al. Recent developments in the use of sodium bicarbonate as an ergogenic aid recent developments in the use of sodium bicarbonate as an ergogenic aid. *Curr Sport Med Rep* 2016; 15(4):233–244. http://dx.doi.org/10.1249/JSR.0000000000000283.
6. Westerblad H. Acidosis is not a significant cause of skeletal muscle fatigue. *Med Sci Sport Exerc* 2016; 48(11):2339–2342.
7. Fitts RH. Cellular mechanisms of muscle fatigue. *Physiol Rev* 1994; 74(1):49–94.
8. Lancha Junior AH, de Salles Painelli V, Saunders B et al. Nutritional strategies to modulate intracellular and extracellular buffering capacity during high-intensity exercise. *Sport Med* 2015; 45(Suppl 1):S71–S81. http://dx.doi.org/10.1007/s40279-015-0397-5.
9. Mainwood G, Worsmey-Brown P. The effects of extracellular pH and buffer concentration on the efflux of lactate from frog sartorius muscle. *J Physiol* 1975; 250:1–22.
10. Granier PL, Dubouchaud H, Mercier BM et al. Effect of $NaHCO_3$ on lactate kinetics in forearm muscles during leg exercise in man. *Med Sci Sport Exerc* 1996; 28(6):692–697.
11. Dalle S, De SmetS, Geuns W et al. Effect of stacked sodium bicarbonate loading on repeated all-out exercise. *Int J Sport Med* 2019; 40(11):711–716.
12. Ferreira LHB, Smolarek AC, Chilibeck PD et al. High doses of sodium bicarbonate increase lactate levels and delay exhaustion in a cycling performance test. *Nutrition* 2019; 60:94–99. http://dx.doi.org/10.1016/j.nut.2018.09.018.
13. McNaughton L, Curtin R, Goodman G et al. Anaerobic work and power output during cycle ergometer exercise: effects of bicarbonate loading. *J Sport Sci* 1991; 9(2):151–160.
14. Grgic J, Rodriguez RF, Garofolini A et al. Effects of sodium bicarbonate supplementation on muscular strength and endurance: a systematic review and meta-analysis. *Sport Med* 2020:0123456789. http://dx.doi.org/10.1007/s40279-020-01275-y.
15. McNaughton LR. Bicarbonate ingestion: effects of dosage on 60 s cycle ergometry. *J Sport Sci* 1992; 10(5):415–423.
16. Wilkes D, Gledhill N, Smyth R. Effect of acute induced metabolic alkalosis on 800-m racing time. *Med Sci Sports Exerc* 1983:277–280. http://dx.doi.org/10.1249/00005768-198315040-00004.
17. Driller M, Gregory J, Williams A et al. The effects of serial and acute $NaHCO_3$ loading in well-trained cyclists. *J Strength Cond Res* 2012; 26(10):2791–2797.
18. Bellinger PM, Howe ST, Shing CM et al. Effect of combined A-alanine and sodium bicarbonate supplementation on cycling performance. *Med Sci Sport Exerc* 2012;(35):1545–1551. http://dx.doi.org/10.1249/MSS.0b013e31824cc08d.
19. Vanhatalo A, McNaughton LR, Siegler J et al. Effect of induced alkalosis on the power-duration relationship of "all-out" exercise. *Med Sci Sports Exerc* 2010; 42(3):563–570. http://dx.doi.org/10.1249/MSS.0b013e3181b71a4a.
20. Durkalec-Michalski K, Zawieja EE, Podg T. The effect of a new sodium bicarbonate loading regimen on anaerobic capacity and wrestling performance. *Nutrients* 2018; 10:697. http://dx.doi.org/10.3390/nu10060697.
21. Durkalec-Michalski K, Zawieja EE, Podgórski T et al. The effect of chronic progressive-dose sodium bicarbonate ingestion on CROSSFIt-like performance: a double-blind, randomized cross-over trial. *PLoS One* 2018; 13(5):1–18. http://dx.doi.org/10.1371/journal.pone.0197480.
22. Pierce EF, Eastman NW, Hammer WH et al. Effect of induced alkalosis on swimming time trials. *J Sports Sci* 1992; 10(3):255–259. http://dx.doi.org/10.1080/02640419208729924.
23. Saunders B, Sale C, Harris RC et al. Sodium bicarbonate and high-intensity-cycling capacity: variability in responses. *Int J Sports Physiol Perform* 2014; 9:627–632.
24. Burke LM. Practical considerations for bicarbonate loading and sports performance. *Nestle Nutr Inst Workshop Ser* 2013; 75:15–26. http://dx.doi.org/10.1159/000345814.
25. Miller P, Robinson AL, Sparks SA et al. The effects of novel ingestion of sodium bicarbonate on repeated sprint ability. *J Strength Cond Res* 2016; 30(2):561–568.
26. Kahle LE, Kelly PV, Eliot KA et al. Acute sodium bicarbonate loading has negligible effects on resting and exercise blood pressure but causes gastrointestinal distress. *Nutr Res* 2013; 33(6):479–486. http://dx.doi.org/10.1016/j.nutres.2013.04.009.
27. De Pauw K, Roelands B, Cheung SS et al. Guidelines to classify subject groups in sport-science research. *Int J Sports Physiol Perform* 2013; 8:111–122. http://dx.doi.org/10.1123/ijspp.2015-0153.
28. Borg G. Perceived exertion as an indicator of somatic stress. *Scand J Rehabil Med* 1970; 2(2):92–98.
29. Pfeiffer B, Cotterill A, Grathwohl D et al. The effect of carbohydrate gels on gastrointestinal tolerance during a 16-km run. *Int J Sport Nutr Exerc Metab* 2009; 19(5):485–503.
30. Cohen J. *Statistical power analysis for the behavioral sciences*, 2nd ed. Lawrence Erlbaum Associates, 1988.
31. George KP, Maclaren DPM. The effect of induced alkalosis and acidosis on endurance running at an intensity corresponding to 4 mM blood lactate. *Ergonomics* 1988; 31(11):1639–1645. http://dx.doi.org/10.1080/00140138808966813.
32. Freis T, Hecksteden A, Such U et al. Effect of sodium bicarbonate on prolonged running performance: A randomized, double- blind, cross-over study. *PLoS One* 2017; 12(8):e0182158.
33. Egger F, Meyer T, Such U et al. Effects of sodium bicarbonate on high-intensity endurance performance in cyclists: a double-blind, randomized. *PLoS One* 2014; 9(12):e114729. http://dx.doi.org/10.1371/journal.pone.0114729.
34. Stephens TJ, McKenna MJ, Canny BJ et al. Effect of sodium bicarbonate on muscle metabolism during intense endurance cycling. *Med Sci Sports Exerc* 2002; 34(4):614–621. http://dx.doi.org/10.1097/00005768-200204000-00009.
35. Mitchell TH, Abraham G, Wing S et al. Intravenous bicarbonate and sodium chloride both prolong endurance during intense cycle ergometer exercise. *Am J Med Sci* 1990; 300(2):88–97.
36. Jones N, Sutton J, Taylor R et al. Effect of pH on cardiorespiratory metabolic responses to exercise. *J Appl Physiol* 1977; 43(6):959–964.
37. Sutton JR, Jones NL, Toews CJ. Effect of pH on muscle glycolysis during exercise. *Clini Sci* 1981; 61(3):331–338. http://dx.doi.org/10.1042/cs0610331.
38. Potteiger JA, Webster MJ, Nickel GL et al. The effects of buffer ingestion on metabolic factors related to distance running performance. *Eur J Appl Physiol* 1996; 72:365–371.
39. Mcnaughton L, Dalton B, Palmer G. Sodium bicarbonate can be used as an ergogenic aid in high-intensity, competitive cycle ergometry of 1h duration. *Eur J Appl Physiol* 1999; 80(1):64–69.
40. Jones RL, Stellingwerff T, Artioli GG et al. Dose-response of sodium bicarbonate ingestion highlights individuality in time course of blood analyte responses. *Int J Sport Nutr Exerc Metab* 2016; 26:445–453.
41. Heibel AB, Perim PHL, Oliveira LF et al. Time to optimize supplementation: modifying factors influencing the individual responses to extracellular buffering agents. *Front Nutr* 2018; 5:35. http://dx.doi.org/10.3389/fnut.2018.00035.
42. Peart DJ, McNaughton LR, Midgley AW et al. Pre-exercise alkalosis attenuates the heat shock protein 72 response to a single-bout of anaerobic exercise. *J Sci Med Sport* 2011; 14(5):435–440. http://dx.doi.org/10.1016/j.jsams.2011.03.006.
43. Juel C. Lactate-proton cotransport in skeletal muscle. *Physiol Rev* 1997; 77(2):321–358.
44. Henderson LJ. The theory of neutrality regulation in the animal organism. *Am J Physiol* 1908; 21(4):427–448.
45. Hirakoba K, Maruyama A, Misaka K. Effect of acute sodium bicarbonate ingestion on excess CO_2 output during incremental exercise. *Eur J Appl Physiol Occup Physiol* 1993; 66(6):536–541.
46. Taylor JL, Amann M, Duchateau J et al. Neural contributions to muscle fatigue: from the brain to the muscle and back again. *Med Sci Sport Exerc* 2017; 48(11):2294–2306. http://dx.doi.org/10.1249/MSS.0000000000000923.Neural.
47. Mitchell JH, Wildenthal K, Johnson RL. The effects of acid–base disturbances on cardiovascular and pulmonary function. *Kidney Int* 1972; 1(5):375–389. http://dx.doi.org/10.1038/ki.1972.48.
48. Wildenthal K, Mierzwiak S, Myers W et al. Efiects of acute lactic acidosis on left ventricular performance. *Am J Physiol* 1968; 214(6):1352–1359.
49. Linden BYRJ, Norman J. The effect of acidaemia on the response to stimulation of the autonomic nerves to the heart. *J Physiol* 1969; 200:51–71.
50. Freyschuss U. Elicitation increase of heart rate and blood on muscle contraction pressure. *J Appl Physiol* 1970; 28(6):758–761.
51. Carr AJ, Slater GJ, Gore CJ et al. Effect of sodium bicarbonate on [HCO_3-], pH, and gastrointestinal symptoms. *Int J Sport Nutr Exerc Metab* 2011; 21(3):189–194. http://dx.doi.org/10.1123/ijsnem.21.3.189.