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Human Kinetics
ORIGINAL INVESTIGATION

No Effect of Individualized Sodium Bicarbonate Supplementation on 200-m or 400-m Freestyle-Swimming Time-Trial Performance in Well-Trained Athletes

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Purpose: This study investigated the effect of an individualized sodium bicarbonate (SB) supplementation-timing strategy on 200-m and 400-m freestyle swimming time-trial (TT) performance. ***Methods:*** Thirteen well-trained swimmers (8 men and 5 women; mean [SD] 22 [3] y, 1.76 [0.79] m, 73.4 [9.6] kg) had their time-to-peak bicarbonate (HCO_3^-) determined after ingestion of 0.3 g·kg^{-1} body mass SB in size 0 vegetarian capsules alongside a carbohydrate-high meal (1.5 g·kg^{-1} body mass). Following familiarization, participants performed 200-m and 400-m freestyle TTs after individualized timing (160 [36] min) of either SB or a placebo (PL; cornflour) on 4 separate occasions in a randomized, double-blind, crossover design. Completion times, blood lactate, and rating of perceived exertion (6–20 Borg) were measured. ***Results:*** SB did not improve completion times compared with PL during the 200-m (124.5 [7.3] vs 125.1 [6.2] s, $P = .219$, $g = 0.09$) or 400-m (263.4 [12.8] vs 264.7 [13.6] s; $P = .192$, $g = 0.10$) TTs. Blood lactate was elevated for SB compared with PL following the 200-m (12.99 [1.45] vs 10.98 [2.25] mmol·L^{-1}; $P = .042$) and 400-m (13.05 [2.29] vs 10.44 [2.40] mmol·L^{-1}; $P = .017$) TTs. SB reduced rating of perceived exertion after the TTs compared with PL (200 m: −0.9 [1.4] au, $P = .033$; 400 m: −1.2 [1.4] au, $P = .012$). ***Conclusions:*** SB consumed in capsules at individualized time-to-peak [HCO_3^-] did not improve 200-m or 400-m freestyle-swimming TT performance and might not be a worthwhile SB ingestion strategy for well-trained swimmers.

Keywords: time to peak, extracellular buffering, ergogenic aids, pacing

High anaerobic energy demand during middle-distance (200 and 400 m) swimming time trials (TTs) produces a buildup of metabolites such as inorganic phosphate and hydrogen ions (H^+) within the muscle.[1] Excessive accumulation of H^+ leads to intramuscular acidosis that may contribute to skeletal-muscle fatigue.[2] In particular, declining muscle pH inhibits adenosine triphosphate (ATP) production via nonoxidative energetic pathways by limiting the rate of glycolysis[3] and cross-bridge cycling formation within skeletal muscles.[4] High blood lactate concentrations (10–15 mmol·L^{-1}) and low blood pH (~7.1 units) following middle-distance swimming TTs are a consequence of high rates of glycolytic flux,[5] suggesting that H^+ accumulation may limit exercise in well-trained swimmers.[2] Ergogenic strategies that act to protect against these biochemical disturbances could, therefore, be vital to optimizing competitive swimming performance.

One popular ergogenic aid for athletes competing in maximal effort exercise is sodium bicarbonate (SB).[6] Empirical evidence exists for the positive effects of SB supplementation on athletic performance.[7] Ingesting 0.3 g·kg^{-1} body mass SB ~90 minutes preexercise typically increases blood bicarbonate (HCO_3^-) concentration by 5 to 6 mmol·L^{-1}, protecting against intramuscular acidosis by raising the pH gradient between intracellular and extracellular environments, allowing greater efflux of H^+ from skeletal musculature into circulation.[8] Concomitantly, elevated intramuscular pH may increase the rate at which ATP is synthesized by offsetting the inhibition of key glycolytic enzymes (ie, phosphofructokinase-1) and aiding skeletal muscle contractility.[3,9] These mechanisms might underpin any small, albeit practically significant, ergogenic effects of SB during swimming.

Placings in middle-distance competitive swimming TTs are often determined by narrow margins, meaning that SB supplementation could be an effective strategy for athletes. Several studies have examined the effect of SB during swimming TTs, but findings are conflicting.[10] Some researchers have observed positive effects for SB,[11,12] whereas others have shown trivial or no improvements.[5,13] These inconsistencies could relate to task duration, with a recent meta-analysis summarizing that SB elicits small, meaningful improvements during middle-distance but not short-distance swimming TTs[10] as accumulation of H^+ is not the primary limiting factor during shorter-duration exercise.[14] There is also evidence that individualizing SB supplementation according to time-to-peak (TTP) [HCO_3^-] increases the likelihood of observing ergogenic benefits.[15] Time course and absolute changes in [HCO_3^-] after SB ingestion differ depending on delivery form, with an elongated window of elevated HCO_3^- bioavailability existing for capsules compared with solution.[16] Although this means that TTP ingestion strategies might be most important when SB is administered in solution, regardless of delivery form, individualized timing ensures that peak [HCO_3^-] occurs immediately preexercise,[17,18] therefore

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maximizing enhanced extracellular buffering capacity during competition events. Notably, previous studies reporting equivocal effects of SB during middle-distance swimming TTs have adopted standardized timing approaches whereby SB was administered between 90 and 120 minutes preexercise.[5,11-13] It is, therefore, possible that researchers missed out on peak changes in [HCO_3^-] following SB ingestion as a high degree of interindividual variation exists.[15,17,18] Additional research is warranted examining whether supplementing SB according to individualized TTP [HCO_3^-] can improve middle-distance swimming TT performance.

Although evidence suggests that task duration is as an important contributing factor for the performance-enhancing effects of SB,[10,14] it is unclear whether differences exist for the ergogenic potential of SB during 2 or more middle-distance swimming TT disciplines. Therefore, the aim of this study was to examine whether an individualized SB supplementation timing strategy was able to improve 200-m and 400-m freestyle swimming TT performance. It was hypothesized that SB would elicit practically meaningful improvements in swimming TT performance in well-trained athletes.

Methods

Study Design

A randomized, double-blind, placebo-controlled, crossover experimental design was employed. Participants had individualized TTP [HCO_3^-] determined after ingesting 0.3 g·kg^{-1} body mass SB and attended 5 pool sessions to perform 200-m or 400-m freestyle swimming TTs (one familiarization, 4 experimental trials). Participants were randomly assigned to receive SB or cornflour (placebo [PL]) using a Latin square sequence.

Participants

A priori sample size calculation revealed that 12 participants would be needed to achieve statistical power ($\beta = 0.85$; $\alpha = .05$). This assumed that a paired samples *t* test would be used to analyze performance and used previous data (effect size [ES] = 0.86) for the effect of SB during 200-m swimming TTs.[11] To account for dropouts, 14 participants were recruited from a high-performance swimming club; however, one withdrew after adverse reactions to SB. Therefore, 13 well-trained swimmers (8 men, 5 women; age: 22 [3] y, stature: 1.76 [0.79] m, body mass: 73.4 [9.6] kg, training frequency per week: 19 [1] h) completed study procedures. All participants (a) regularly competed in middle-distance swimming events, (b) had not used extracellular or intracellular buffers in the previous 6 months, and (c) were not allergic to cornflour. Female participants performed procedures across different phases of their menstrual cycle as only a trivial ES exists for the influence of menstrual cycle phase on exercise performance.[19] Procedures were approved by the institutional ethics committee (ER48939174) and conducted according to the revised Declaration of Helsinki. Participants provided written informed consent before commencing the study.

Procedures

Participants attended sessions in a 3-hour postprandial state having avoided alcohol and caffeine for 12 hours. Swimming TTs were performed in an Olympic-sized pool (dimensions: 2-m deep × 50-m long × 20-m wide; water temperature: 30 °C). Experimental trials were separated by 5 to 7 days to ensure appropriate washout of treatments. Testing was conducted during training hours (1400–1730 h) to control for the confounding effect of circadian rhythms on exercise performance.[20] Participants were asked to replicate dietary practices 24 hours before experimental trials and wear the same swimming costume for each session.

During the preliminary laboratory visit, anthropometric measures were recorded before participants had TTP [HCO_3^-] measured. Following baseline blood samples, participants ingested 0.3 g·kg^{-1} body mass SB alongside a carbohydrate-high meal across a 30-minute period. Additional blood samples were measured 80-minutes postconsumption and then every 20 minutes until peak [HCO_3^-] was achieved.

Participants performed a familiarization session for the 200-m and 400-m freestyle swimming TTs. They underwent a 26-minute pool-based warm-up (1600 m) led by their coach. Participants were given 15 minutes between finishing the warm-up and starting TTs to change into their race costume. Both the 200-m and 400-m TTs comprised a dive start using racing blocks and were timed on a handheld digital stopwatch (PC2810, JZK) by a British Swimming accredited coach. Handheld stopwatches are considered a suitable alternative to electronic timing systems when collecting group-level data (intraclass correlation coefficient [ICC]: $r = .99$).[21] Participants were given 10-minute recovery between the 200-m and 400-m TTs.

On arrival during experimental trials, baseline capillary blood samples and gastrointestinal discomfort visual analog scale (VAS) were measured. Participants then consumed supplements (either SB or cornflour) and the carbohydrate meal across a 30-minute period. Timing of supplements prior to swimming TTs was based on participants' TTP [HCO_3^-]. Gastrointestinal discomfort VAS and treatment assignment questionnaires were filled in postconsumption. Additional water provided to participants ad libitum (616 [198] mL) was replicated during experimental trials. Capillary blood samples, gastrointestinal discomfort VAS, and treatment assignment questions were repeated prewarm-up. Participants started the warm-up 41 minutes before performing the 200-m or 400-m swimming TTs. They were provided a heart rate monitor (Verity Sense, Polar). Capillary blood samples and rating of perceived exertion (RPE; Borg 6–20) were measured postwarm-up and post-TT. Participants started swimming TTs at the point corresponding with their TTP [HCO_3^-]. Time to completion and pacing (50-m splits for 200 m; 100-m splits for 400 m) were recorded during TTs. Gastrointestinal discomfort VAS and treatment assignment questionnaires were repeated post-TT.

Supplementation Protocol

Participants ingested 0.3 g·kg^{-1} body mass SB (Health Leads Ltd) or cornflour (PL; Sainsburys) in an equal number of size 0 vegetarian capsules (Your Supplements). Cornflour was chosen as the PL, as it is an inert substance that adequately blinds SB.[22] Capsules were manually filled using a capsule-filling machine (ALL-IN Capsule) and contained ~0.8 g SB or ~0.4 g cornflour. Capsules were given to the nearest whole number (28 [4]) and were administered with 7 mL·kg^{-1} body mass water as 3 equal doses across a 30-minute window alongside the carbohydrate-high meal (1.5 g·kg^{-1} body mass; biscuits, cereal bars, cornflakes with milk).[23]

Blood Sampling

During the preliminary laboratory session, finger prick capillary blood samples (95 µL) were analyzed using a portable blood gas analyzer (i-STAT Alinity) to determine [HCO_3^-]. Previous

research has suggested that this analyzer demonstrates moderate-to-good reliability for HCO_3^- measured at rest (ICC: $r = .81$; typical error of measurement, TEM: 2.2%) and during submaximal exercise (ICC: $r = .66$; TEM: 3.8%) when mean values are ~25 mmol·L^{-1}.[24] Capillary blood samples (20 µL) were collected into hemolyzing cups (EKF Diagnostics) and analyzed for lactate using a Biosen C-Line (EKF Diagnostics; within-day coefficient variance, CV: < 1.5% at a value of 12 mmol·L^{-1}) during experimental trials.

Questionnaires

Throughout swimming TTs, participants completed questionnaires that required them to indicate which treatment they thought had been administered ("SB," "PL," "unsure").[22] Participants also completed 100 mm VAS (VAS; "0" = no symptom, "100" = severest symptom) to calculate aggregate gastrointestinal discomfort (out of 800 mm) for 8 common side effects.[25]

Statistical Analysis

Grouped data and standardized residuals were assessed for normality using Shapiro–Wilks tests. Homogeneity of variance/sphericity was analyzed using Mauchly tests, and any violations were corrected via Greenhouse–Geisser adjustments. In an attempt to determine the reproducibility of swimming TT performance, % TEM and ICCs were calculated between familiarization and PL for a subgroup of participants (n = 9; due to limited access to the swimmers, familiarization sessions were performed in 2 batches, but unfortunately, data were lost for batch 2). Two-way mixed model, absolute agreement ICCs were interpreted as poor ($r < .50$), moderate ($r = .50$–$.75$), good ($r = .75$–$.90$), or excellent ($r > .90$).[26] Two-way repeated-measures analyses of variance were used to determine treatment × time interactions for blood lactate and TT pacing. When significant effects were found, post hoc pairwise comparisons were made using Bonferroni correction factors. Paired samples t tests were used to analyze TT completion times, RPE, and heart rate. Order effects were also assessed via paired t tests by comparing completion times from the first and second time each TT event was performed. Pearson correlation coefficients were used to explore the relationship between aggregate gastrointestinal discomfort and improvements in swimming TT performance, with coefficients interpreted according to conventional approaches.[27] To determine individual changes in TT performance, the smallest worthwhile change (SWC) statistic was used (0.3 × between-subject SD).[28] To determine the variability in HCO_3^- pharmacokinetics data after SB ingestion, CV was calculated for peak concentration (C_{max}), absolute change in concentration ($\Delta\ C_{max}$), and TTP from the preliminary testing session ((SD/mean) × 100). Partial eta squared (η_p^2) was used as the ES for analysis of variance main effects and interactions. Between-treatment ES was calculated by dividing mean difference by the pooled SD before applying Hedges g (g) bias correction to account for the small sample size.[29] These were interpreted as trivial (≤0.20), small (0.20–0.49), moderate (0.50–0.79), or large (≥0.80).[30] Friedman tests were used to analyze aggregate gastrointestinal discomfort (normal distribution violated), with median, interquartile range, and Z values reported. Treatment assignment ratings for SB and PL were analyzed using 2 × 2 chi-square tests (χ^2) to determine blinding efficacy. Data are presented as mean (SD) (unless stated; median [interquartile range]) with 95% confidence intervals (CI) reported for mean differences. Statistical significance was set at $P < .05$. All data were analyzed using SPSS (26.0, IBM).

Results

Time-to-Peak [HCO_3^-] Pharmacokinetics

From the preliminary session, C_{max} was 34.2 (1.8) mmol·L^{-1} (CV = 5.2%, range: 31.7–38.7 mmol·L^{-1}). Likewise, $\Delta\ C_{max}$ was 8.9 (1.7) mmol·L^{-1} (CV = 19.1%, range: 6.3–12.0 mmol·L^{-1}), and TTP [HCO_3^-] was 160 (36) minutes (CV = 22%, range: 80–220 min) (Table 1).

Swimming Time-Trial Performance

Completion times were highly reproducible, with the 200-m and 400-m TTs showing low TEM (2.5%, 1.3%) and good-to-excellent ICCs ($r = .83, .91$). No significant differences were reported for 200-m TT completion times for SB compared with PL (124.5 [7.3] vs 125.1 [6.2] s; $t(12) = 1.297$, $P = .219$, $g = 0.09$), with only 3 participants improving above the SWC (Figure 1A). No significant differences were reported for 400-m TT completion times for SB

Table 1 Individual Pharmacokinetic Responses for Blood Bicarbonate After SB Ingestion During the Preliminary Testing Session

Participant	TTP, min	C_{max}, mmol·L^{-1}	$\Delta\ C_{max}$, mmol·L^{-1}
1	160	34.0	6.3
2	160	36.2	8.5
3	160	38.7	12.0
4	200	34.0	8.8
5	80	32.2	8.2
6	120	31.7	7.0
7	160	34.5	8.6
8	180	32.9	6.8
9	180	34.8	9.3
10	220	32.9	9.5
11	140	34.7	8.8
12	180	32.8	10.2
13	140	34.5	11.6
Mean	160	34.2	8.9
SD	36	1.8	1.7
CV	22	5.2	19.1

Abbreviations: $\Delta\ C_{max}$, absolute change in concentration; C_{max}, peak concentration; CV, coefficient variance; TTP, time to peak.

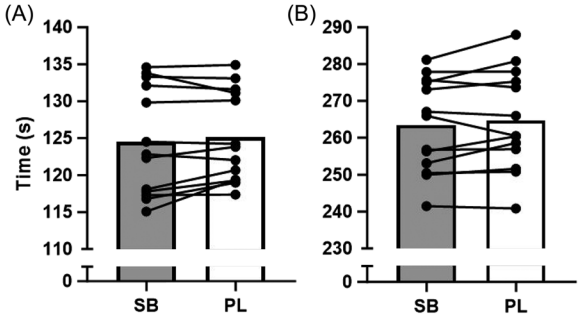

Figure 1 — Mean and interindividual variation for completion times during the 200-m (A) and 400-m (B) freestyle-swimming time trials after ingestion of SB and PL. PL indicates placebo; SB, sodium bicarbonate.

compared with PL (263.4 [12.8] vs 264.7 [13.6] s; $t(12) = 1.382$, $P = .192$, $g = 0.10$), with only 4 participants improving above the SWC (Figure 1B).

No 2-way treatment × time interactions existed for pacing during the 200-m ($F_{3,\ 36} = 0.082$, $P = .969$, $\eta_p^2 = .007$), or 400-m ($F_{1.2,\ 14.6} = 0.627$, $P = .472$, $\eta_p^2 = .050$) TTs, but main effects of time (200-m: $F_{3,\ 36} = 194.961$, $P < .001$, $\eta_p^2 = .942$; 400-m: $F_{1.3,\ 15.4} = 127.465$, $P < .001$, $\eta_p^2 = .914$) were reported. The first splits during the 200-m (50-m) and 400-m (100 m) TTs were faster for SB and PL compared with subsequent splits (all $P < .001$), but there was no difference between treatments (200-m: $P = .674$; 400-m: $P = .909$) (Figure 2A and 2B).

Despite an unbalanced randomization due to participant dropout (n = 1), no order effects were observed for the swimming TTs (200-m: $t(12) = 1.333$, $P = .207$; 400-m: $t(12) = .163$, $P = .874$). Grouped completion times were similar regardless of what order participants performed 200-m (0.65-s faster for trial 1, $g = 0.09$) and 400-m (0.17-s faster for trial 2, $g = 0.01$) TTs for each treatment.

Blood Lactate

There was a 2-way treatment × time interaction for blood lactate ($F_{4.3,\ 50.7} = 6.635$, $P < .001$, $\eta_p^2 = .356$). Blood lactate was similar between treatments postwarm-up ($F_{3,\ 36} = 2.403$, $P = .084$, $\eta_p^2 = .167$) but was elevated for SB compared with PL after the 200-m (+2.0 mmol·L^{-1}, 95% CI, 0.6 to 4.0, $P = .042$, $g = 1.03$) and 400-m (+2.6 mmol·L^{-1}, 95% CI, 0.4 to 4.8, $P = .017$, $g = 1.08$) TTs (Figure 3).

RPE and Heart Rate

Postwarm-up RPE was similar between SB and PL during the 200-m ($t(12) = 1.066$, $P = .307$) and 400-m ($t(12) = 1.10$, $P = .293$) TTs. SB reduced RPE compared with PL after the 200-m (–0.9 [1.4] au, 95% CI, –1.8 to –0.1; $t(12) = 2.408$, $P = .033$, $g = 0.83$) and 400-m (–1.2 [1.4] au, 95% CI, –2.0 to –0.3; $t(12) = 2.961$, $P = .012$, $g = 0.95$) TTs (Table 2). No differences were observed between SB and PL for heart rate during the 200-m (average: $t(12) = .271$, $P = .791$; maximum: $t(12) = .450$, $P = .661$) or 400-m (average: $t(12) = .972$, $P = .350$; maximum: $t(12) = .475$, $P = .643$) TTs.

Gastrointestinal Discomfort and Blinding

There was an effect of treatment on aggregate gastrointestinal discomfort prewarm-up ($\chi^2(3) = 11.319$, $P = .010$) and post-TT ($\chi^2(3) = 9.314$, $P = .026$) (Table 3). Aggregate gastrointestinal discomfort was higher for SB compared with PL prewarm-up during the 200-m TT ($Z = 1.500$, $P = .018$) and after the 400-m TT compared with the 200-m TT ($Z = 1.385$, $P = .037$). Severity of post-TT aggregate gastrointestinal discomfort for SB was not correlated with improvements in 200-m, $r(13) = –.052$, $P = .867$, or 400-m, $r(13) = –.109$, $P = .724$, TT completion times (Figure 4A and 4B).

During the 200-m TTs, the number of correct guesses was similar between treatments postconsumption (SB and PL: 4/13), prewarm-up (SB: 6/13, PL: 5/13), and post-TT (SB: 4/13, PL: 6/13). The number of correct guesses was similar between treatments postconsumption during the 400-m TTs ($P = .420$), but there were

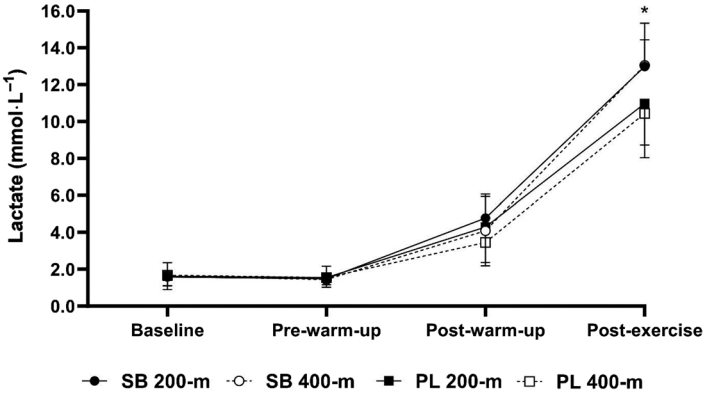

Figure 3 — Mean (SD) blood-lactate response from baseline to postexercise for SB and PL. *Higher than PL ($P < .05$). PL indicates placebo; SB, sodium bicarbonate.

Table 2 Rating of Perceived Exertion (Arbitrary Units) During Time Trials, Mean (SD)

	Post-warm-up	Post–time trial
200-m time trial		
Sodium bicarbonate	12.5 (1.6)	16.8 (0.7)*
Placebo	13.0 (2.0)	17.7 (1.3)
400-m time trial		
Sodium bicarbonate	13.1 (1.4)	17.2 (1.3)*
Placebo	12.7 (1.3)	18.3 (1.3)

*Lower than placebo ($P < .05$).

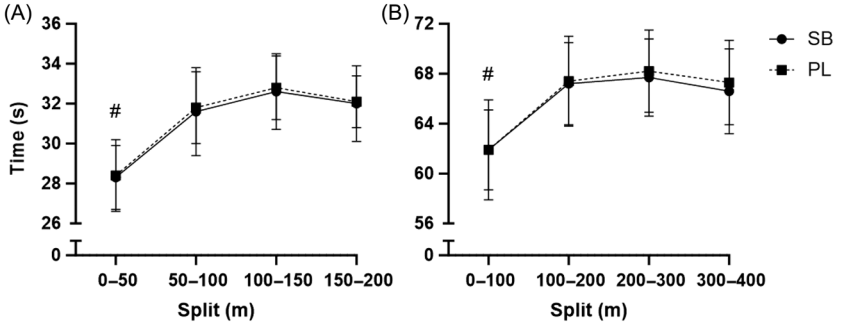

Figure 2 — Mean (SD) pacing during the 200-m (A; 50-m splits) and 400-m (B; 100-m splits) freestyle-swimming time trials after ingestion of SB and PL. #Faster than subsequent splits ($P < .05$). PL indicates placebo; SB, sodium bicarbonate.

Table 3 Aggregate Gastrointestinal-Discomfort Score From Baseline to Post–Time Trial

	Baseline	Postsupplementation	Pre-warm-up	Post–time trial
200-m time trial				
Sodium bicarbonate	17.0 (14.0)	46.0 (47.5)	30.0 (51.0)	32.0 (75.5)
Placebo	19.0 (6.5)	24.0 (38.0)	29.0 (51.0)	24.0 (44.5)
400-m time trial				
Sodium bicarbonate	24.0 (16.5)	40.0 (56.0)	83.0 (70.5)*	86.0 (71.0)#
Placebo	23.0 (10.5)	45.0 (29.5)	25.0 (38.0)	50.0 (53.0)

Note: Values presented as median (interquartile range). Aggregate gastrointestinal-discomfort score (out of 800 mm) calculated from sum of visual analogue scale for 8 symptoms.
*Greater than PL during the 400-m TT ($P < .05$). #Greater than PL during the 200-m TT ($P < .05$).

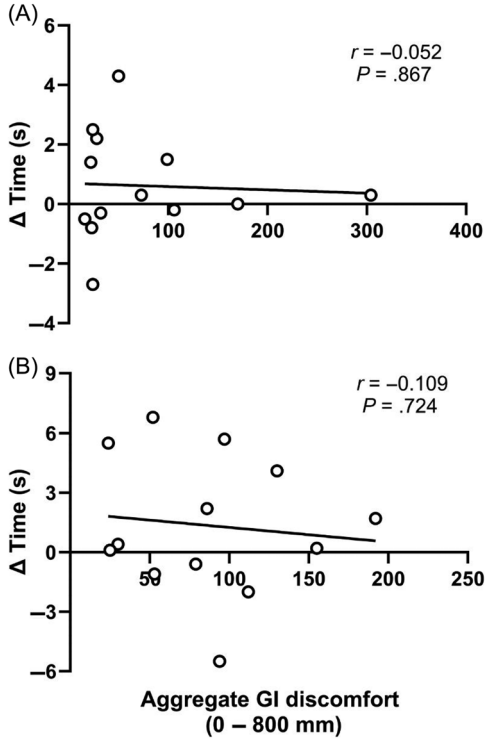

Figure 4 — Relationship between aggregate GI discomfort (scored out of 800 mm; sum of 8 symptoms) and improvements in completion time for sodium bicarbonate compared with placebo during the 200-m (A) and 400-m (B) swimming time trials. Pearson correlation coefficient (r) and significance value (P) are reported. GI indicates gastrointestinal.

more correct ratings for SB compared with PLA prewarm-up (SB: 8/13, PL: 3/13; $\chi^2(1) = 3.939$, $P = .047$) and post-TT (SB: 8/13, PL: 1/13; $\chi^2(1) = 6.993$, $P = .008$).

Discussion

The aim of this study was to examine whether an individualized SB supplementation timing strategy was able to improve 200-m and 400-m freestyle swimming TT performance. Neither 200-m nor 400-m TT completion times nor pacing was faster following SB compared with PL in this cohort of well-trained athletes, with fewer than 25% of participants reporting improvements above the SWC. Exacerbated gastrointestinal discomfort was reported pre-warm-up and post-TT following SB, but there were no significant correlations between the severity of gastrointestinal discomfort and improvements in swimming TT performance. Elevated blood lactate postexercise and attenuated RPE during the TTs for SB suggest that the supplement could still have some practical implications during competitive swimming. Considering the challenges associated with blood gas analysis, it might not be worthwhile for swimmers to align SB timing with predetermined HCO_3^- pharmacokinetics when a capsule ingestion form is chosen, but further research comparing standardized and individualized SB timing approaches is needed.

No improvements were observed for time to completion during the 200-m or 400-m swimming TTs after SB, with only a trivial ES compared with PL. This is consistent with findings from some studies[5,13] but not others.[11,12] As we did not measure blood pH and HCO_3^- throughout the swimming TTs, it is possible that elevated extracellular buffering for SB was partially utilized during the warm-up, subsequently reducing ergogenic effects in the swimming TTs.[17] On the other hand, we theorized that greater benefits might exist for SB during the 400-m TT as performance-enhancing effects of SB are more pronounced during maximal exercise tasks lasting 4 to 8 minutes compared with between 1 and 4 minutes.[14] Rapid rate of intramuscular pH decline during shorter maximal exercise tests causes the monocarboxylate transporter 1/4 to become oversaturated with H^+, in turn limiting the beneficial effects of enhanced HCO_3^- buffering.[3] It was, therefore, surprising that improvements were not observed for SB during the 400-m TT. As both male and female swimmers were recruited, one explanation for this could relate to gender-specific physiological differences that mechanistically underpin the efficacy of SB.[31] In short, males may exhibit greater benefits following SB supplementation[31] as they have larger type II muscle fibers that rely heavily on glycolytic pathways for ATP production,[32] meaning that they, theoretically, have more to gain from SB. The present study did not specifically aim to examine gender-specific responses for the effect of SB, but further work is required to understand how physiological differences between males and females may impact the efficacy of SB during whole-body swimming exercise.

This study was the first to show no performance-enhancing effects for individualized SB supplementation. In agreement with previous research,[17,18,33] a large degree of interindividual variation existed for TTP [HCO_3^-] after SB. Aligning SB ingestion timing with predetermined TTP [HCO_3^-] maximizes the likelihood of performance benefits,[15] as it ensures that peak changes achieve the 5 to 6 mmol·L^{-1} increase considered vital to ergogenic effects.[34] Changes in [HCO_3^-] after SB from the preliminary testing exceeded this "ergogenic" threshold for all participants (range: 6.3–12.0 mmol·L^{-1}), but less than 25% of participants improved above

the SWC during the 200-m (3/13) and 400-m (4/13) TTs. As previous research suggests that TTP [HCO_3^-] might not be reproducible when SB is consumed in capsule form,[35] it is possible that some participants began TTs at a time point not corresponding to their individualized peak [HCO_3^-]. Furthermore, no improvements were shown for TT pacing, with 50-m and 100-m split times similar between SB and PL, which contradicts recent findings after SB during 3.5-km running TTs.[33] One reason for the discrepancies in results could be that not all the participants were familiar with 200-m and 400-m freestyle swimming TTs as some claimed that neither was their preferred discipline. In these instances, one familiarization session might not have been enough for participants to develop a stable pacing strategy between treatments,[36] meaning that day-to-day variability in their performance masked any small, albeit meaningful, improvements for SB.[28] Alternatively, the absence of performance benefits for SB could be explained by the whole-body nature of swimming.[10] It has been suggested that the ergogenic effects of SB are greater in exercise tasks using smaller muscles groups or fewer muscle groups.[37] This hypothesis assumes that the higher proportion of total blood flow to active musculature during isolated muscle group (eg, maximal leg extensions) or predominately lower-limb (eg, cycling, running) exercise allows for greater ion exchange between intracellular and extracellular environments.[37] On the other hand, during whole-body exercise such as swimming, blood flow (and, thus, HCO_3^- delivery) is distributed to numerous muscle groups (eg, hamstrings, biceps, forearms). This may result in the localized effects of elevated blood buffering capacity (ie, reduced pain sensation at active muscles)[38] being less noticeable as circulating HCO_3^- is delivered across a larger body surface area, meaning that ergogenic benefits for SB are diminished.

Participants reported greater gastrointestinal discomfort for SB compared with PL prewarm-up and post-TT, despite a split dose ingestion strategy being employed to reduce side effects.[23] It remains disputed whether side effects after SB are detrimental to exercise performance,[25,39,40] but no correlations existed between the severity of gastrointestinal discomfort and improvements in swimming TT performance. That being said, studies demonstrating ergogenic benefits for individualized SB have reported minimal gastrointestinal discomfort,[18,33] meaning that it cannot be ruled out that side effects diminish performance benefits for SB. Exacerbated gastrointestinal side effects for this cohort of swimmers might be attributed to differences in administration approach as previous studies gave SB in enteric-coated capsules[33] and as smaller 0.2 $g \cdot kg^{-1}$ body mass doses[18] that further mitigate gastrointestinal discomfort. Interestingly, aggregate gastrointestinal discomfort was also high for PL after the 400-m TT, suggesting that side effects might not only have been due to SB. As participants consumed the carbohydrate-high meal alongside capsules, it is possible that exacerbated gastrointestinal symptoms for PL can be explained by food not being digested prior to exercise.[41] This was likely particularly pertinent to participants displaying a shorter TTP [HCO_3^-] as, in some instances, their meal had to be consumed less than 60 minutes before starting the warm-up.

Blood lactate was significantly elevated for SB compared with PL after the 200-m and 400-m swimming TTs. Absolute differences in postexercise blood lactate for SB (~2.5 $mmol \cdot L^{-1}$) were similar to some studies[5,11] but not others[13] examining the ergogenic effects of SB during middle-distance swimming TTs. Although changes in blood acid–base balance were not measured during experimental trials, it is logical to assume that SB elevated blood pH and [HCO_3^-] preexercise, which protected against declining intramuscular pH during exercise.[8] In particular, greater postexercise blood lactate suggests that SB upregulated lactate–H^+ cotransport from active musculature via the monocarboxylate transporters, theoretically preventing intramuscular acidosis from inhibiting key glycolytic and, thus, augmenting ATP production from anaerobic glycolysis.[3] As higher postexercise blood lactate for SB is only an indirect measure of upregulated glycolytic flux,[3] increases greater than 2.0 $mmol \cdot L^{-1}$ are often cited as being required to attribute ergogenic effects of extracellular buffering aids to changes in energy system contribution.[25] Despite differences in postexercise blood lactate between treatments being above this threshold, no ergogenic effects were reported during the swimming TTs, supporting earlier claims that augmented metabolic flux after SB may not always contribute toward performance benefits.[39,42] It is believed that alternative physiological mechanisms, such as greater regulation of intracellular and extracellular strong ion concentration after SB ingestion, also underpin ergogenic effects.[37,43]

The present study found lower RPE during the swimming TTs for SB compared with PL without any changes in heart rate. These results add to previous equivocal findings for the effect of SB on RPE[39,43,44] and support evidence that SB may also act via centrally mediated mechanisms.[38] Attenuated RPE for SB has typically been linked to the deleterious effects of intramuscular acidosis on localized pain sensation during intense exercise.[39,43] In short, SB leads to peripheral alterations (ie, fewer H^+ in the muscle) that are thought to modulate activation of groups III and IV muscle afferents, thus reducing negative feedback from muscles and sustaining drive to motor neurons.[38] However, reduced RPE for SB did not translate to improved performance during the swimming TTs. Some participants were able to identify that SB had been given, meaning that they might have subconsciously rated swimming TTs as easier because of preestablished beliefs that SB would reduce perception of effort during exercise,[42] thus lowering RPE without any ergogenic effects.

Practical Applications

Ingestion of 0.3 $g \cdot kg^{-1}$ body mass SB in capsules did not significantly improve 200-m or 400-m freestyle swimming TT performance in well-trained athletes. Despite aligning SB supplementation timing with predetermined TTP [HCO_3^-], only a few participants reported improvements in completion times above the SWC, suggesting that the logistical and financial challenges of establishing HCO_3^- pharmacokinetics after SB ingestion may outweigh potential ergogenic benefits during middle-distance swimming TTs. On the other hand, reduced RPE observed post-TT for SB could have important "real-world" implications for swimmers during repeated training sessions and multiple competition events performed on the same day.[45] One limitation of this study was not measuring blood pH and [HCO_3^-] during swimming TTs. Due to financial restrictions, it was only possible to determine TTP [HCO_3^-] after SB ingestion during a preliminary laboratory visit and not changes in blood acid–base balance throughout experimental trials. This meant that it was not possible to comment on the repeatability of changes in [HCO_3^-] for individualized SB ingestion or theorize whether the lack of performance benefits for SB could be attributed to participants failing to consistently achieve increases that exceeded the 5 to 6 $mmol \cdot L^{-1}$ "ergogenic" threshold.[34] Furthermore, exacerbated gastrointestinal discomfort after SB might deter athletes from using the supplement regardless of whether side effects are

detrimental to performance; therefore, practitioners need to carefully consider administration strategies and timing of preexercise meals to minimize severity of gastrointestinal discomfort. Attempting to individualize SB timing for well-trained swimmers competing in middle-distance TTs does not appear to be worthwhile when a capsule SB ingestion form is chosen, but further research comparing standardized and individualized timing approaches is needed.

Conclusion

Middle-distance freestyle-swimming time-trial (TT) completion times and pacing were not faster after ingestion of 0.3 $g \cdot kg^{-1}$ body mass sodium bicarbonate (SB), but higher blood lactate postexercise and lower rating of perceived exertion during the TTs were observed following SB. This was the first study to demonstrate that individualizing SB supplementation according to time to peak [HCO_3^-] did not elicit performance benefits, with only a few of the well-trained swimmers reporting meaningful improvements during 200-m and 400-m swimming TTs. Exacerbated gastrointestinal discomfort was observed for SB compared with placebo pre-warm-up and post-TT, but there were no correlations between symptom severity and improvements in swimming TT performance, suggesting that gastrointestinal side effects do not directly impair ergogenic effects. In summary, individualizing SB timing according to predetermined HCO_3^- pharmacokinetics might not be a worthwhile strategy for well-trained swimmers when a capsule SB ingestion form is chosen, given the logistical and financial challenges of blood gas analysis. Additional research is required comparing the ergogenic effects of standardized and individualized SB timing approaches to further refine recommendations for practitioners seeking to improve middle-distance swimming TT performance in well-trained athletes.

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References

1. Sahlin K. Muscle energetics during explosive activities and potential effects of nutrition and training. *Sports Med*. 2014;44(2):167–173. doi:10.1007/s40279-014-0256-9
2. Fitts RH. The role of acidosis in fatigue: pro perspective. *Med Sci Sports Exerc*. 2016;48(11):2335–2338. doi:10.1249/mss.0000000000001043
3. Messonnier L, Kristensen M, Juel C, Denis C. Importance of pH regulation and lactate/H+ transport capacity for work production during supramaximal exercise in humans. *J Appl Physiol*. 2007;102(5):1936–1944. doi:10.1152/japplphysiol.00691.2006
4. Debold EP, Beck SE, Warshaw DM. Effect of low pH on single skeletal muscle myosin mechanics and kinetics. *Am J Physiol-Cell Physiol*. 2008;295(1):C173–C179. doi:10.1152/ajpcell.00172.2008
5. Pruscino CL, Ross MLR, Gregory JR, Savage B, Flanagan TR. Effects of sodium bicarbonate, caffeine, and their combination on repeated 200-m freestyle performance. *Int J Sport Nutr Exerc Metab*. 2008;18(2):116–130.
6. Maughan RJ, Burke LM, Dvorak J, et al. IOC consensus statement: dietary supplements and the high-performance athlete. *Int J Sport Nutr Exerc Metab*. 2018;28(2):104–125. doi:10.1123/ijsnem.2018-0020
7. de Oliveira LF, Dolan E, Swinton PA, et al. Extracellular buffering supplements to improve exercise capacity and performance: a comprehensive systematic review and meta-analysis. *Sports Med*. 2022;52(3):505–526. doi:10.1007/s40279-021-01575-x
8. Bishop D, Edge J, Davis C, Goodman C. Induced metabolic alkalosis affects muscle metabolism and repeated-sprint ability. *Med Sci Sports Exerc*. 2004;36(5):807–813. doi:10.1249/01.MSS.0000126392.20025.17
9. Hollidge-Horvat MG, Parolin ML, Wong D, Jones NL, Heigenhauser GJF. Effect of induced metabolic alkalosis on human skeletal muscle metabolism during exercise. *Am J Physiol-Endocrinol Metab*. 2000;278(2):E316–E329. doi:10.1152/ajpendo.2000.278.2.E316
10. Grgic J, Mikulic P. Ergogenic effects of sodium bicarbonate supplementation on middle-, but not short-distance swimming tests: a meta-analysis. *J Diet Suppl*. 2022;19(6):791–802. doi:10.1080/19390211.2021.1942381
11. Lindh A, Peyrebrune M, Ingham S, Bailey D, Folland J. Sodium bicarbonate improves swimming performance. *Int J Sports Med*. 2008;29:519–523. doi:10.1055/s-2007-989228
12. de Salles Painelli V, Roschel H, de Jesus F, et al. The ergogenic effect of beta-alanine combined with sodium bicarbonate on high-intensity swimming performance. *Appl Physiol Nutr Metab*. 2013;38(5):525–532. doi:10.1139/apnm-2012-0286
13. Joyce S, Minahan C, Anderson M, Osborne M. Acute and chronic loading of sodium bicarbonate in highly trained swimmers. *Eur J Appl Physiol*. 2012;112(2):461–469. doi:10.1007/s00421-011-1995-z
14. Hadzic M, Eckstein ML, Schugardt M. The impact of sodium bicarbonate on performance in response to exercise duration in athletes: a systematic review. *J Sports Sci Med*. 2019;18(2):271–281.
15. Boegman S, Stellingwerff T, Shaw G, et al. The impact of individualizing sodium bicarbonate supplementation strategies on world-class rowing performance. *Front Nutr*. 2020;7:138. Accessed February 15, 2023. https://www.frontiersin.org/articles/10.3389/fnut.2020.00138
16. Hilton NP, Leach NK, Sparks SA, et al. A novel ingestion strategy for sodium bicarbonate supplementation in a delayed-release form: a randomised crossover study in trained males. *Sports Med Open*. 2019;5(1):4. doi:10.1186/s40798-019-0177-0
17. Gurton WH, Faulkner SH, James RM. Effect of warm-up and sodium bicarbonate ingestion on 4-km cycling time-trial performance. *Int J Sports Physiol Perform*. 2021;16(11):1573–1579. doi:10.1123/ijspp.2020-0743
18. Gough LA, Williams JJ, Newbury JW, Gurton WH. The effects of sodium bicarbonate supplementation at individual time-to-peak blood bicarbonate on 4-km cycling time trial performance in the heat. *Eur J Sport Sci*. 2022;22(12):1856–1864. doi:10.1080/17461391.2021.1998644
19. McNulty KL, Elliott-Sale KJ, Dolan E, et al. The effects of menstrual cycle phase on exercise performance in eumenorrheic women: a systematic review and meta-analysis. *Sports Med Auckl Nz*. 2020;50(10):1813–1827. doi:10.1007/s40279-020-01319-3
20. Reilly T. Human circadian rhythms and exercise. *Crit Rev Biomed Eng*. 1990;18(3):165–180.
21. Hetzler RK, Stickley CD, Lundquist KM, Kimura IF. Reliability and accuracy of handheld stopwatches compared with electronic timing in measuring sprint performance. *J Strength Cond Res*. 2008;22(6):1969. doi:10.1519/JSC.0b013e318185f36c

22. Gurton WH, Matta GG, Gough LA, Hurst P. Efficacy of sodium bicarbonate ingestion strategies for protecting blinding. *Eur J Appl Physiol*. 2022;122(12):2555–2563. doi:10.1007/s00421-022-05031-0
23. Carr A, Slater G, Gore C, Dawson B, Burke L. Effect of Sodium Bicarbonate on [HCO_3^-], pH, and gastrointestinal symptoms. *Int J Sport Nutr Exerc Metab*. 2011;21:189–194. doi:10.1123/ijsnem.21.3.189
24. Dascombe BJ, Reaburn PRJ, Sirotic AC, Coutts AJ. The reliability of the i-STAT clinical portable analyser. *J Sci Med Sport*. 2007;10(3):135–140. doi:10.1016/j.jsams.2006.05.023
25. Gurton WH, Gough LA, Sparks SA, Faghy MA, Reed KE. Sodium bicarbonate ingestion improves time-to-exhaustion cycling performance and alters estimated energy system contribution: a dose-response investigation. *Front Nutr*. 2020;7:154. Accessed April 4, 2023. https://www.frontiersin.org/articles/10.3389/fnut.2020.00154
26. Koo TK, Li MY. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *J Chiropr Med*. 2016;15(2):155–163. doi:10.1016/j.jcm.2016.02.012
27. Schober P, Boer C, Schwarte LA. Correlation coefficients: appropriate use and interpretation. *Anesth Analg*. 2018;126(5):1763. doi:10.1213/ANE.0000000000002864
28. Paton CD, Hopkins WG. Variation in performance of elite cyclists from race to race. *Eur J Sport Sci*. 2006;6(1):25–31. doi:10.1080/17461390500422796
29. Lakens D. Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs. *Front Psychol*. 2013;4:863. Accessed August 2, 2022. https://www.frontiersin.org/articles/10.3389/fpsyg.2013.00863
30. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. 2nd ed. Routledge; 1988. doi:10.4324/9780203771587
31. Durkalec–Michalski K, Zawieja EE, Zawieja BE, Michałowska P, Podgórski T. The gender dependent influence of sodium bicarbonate supplementation on anaerobic power and specific performance in female and male wrestlers. *Sci Rep*. 2020;10(1):1878. doi:10.1038/s41598-020-57590-x
32. Simoneau JA, Bouchard C. Human variation in skeletal muscle fiber-type proportion and enzyme activities. *Am J Physiol-Endocrinol Metab*. 1989;257(4):E567–E572. doi:10.1152/ajpendo.1989.257.4.E567
33. Lassen TAH, Lindstrøm L, Lønbro S, Madsen K. Increased performance in elite runners following individualized timing of sodium bicarbonate supplementation. *Int J Sport Nutr Exerc Metab*. 2021;31(6):453–459. doi:10.1123/ijsnem.2020-0352
34. Carr AJ, Hopkins WG, Gore CJ. Effects of acute alkalosis and acidosis on performance. *Sports Med*. 2011;41(10):801–814. doi:10.2165/11591440-000000000-00000
35. Farias De Oliveira L, Saunders B, Yamaguchi G, Swinton P, Giannini Artioli G. Is individualization of sodium bicarbonate ingestion based on time to peak necessary? *Med Sci Sports Exerc*. 2020;52(8):1801–1808. doi:10.1249/MSS.0000000000002313
36. Thomas K, Stone MR, Thompson KG, St Clair Gibson A, Ansley L. Reproducibility of pacing strategy during simulated 20-km cycling time trials in well-trained cyclists. *Eur J Appl Physiol*. 2012;112(1):223–229. doi:10.1007/s00421-011-1974-4
37. Sostaric SM, Skinner SL, Brown MJ, et al. Alkalosis increases muscle K+ release, but lowers plasma [K+] and delays fatigue during dynamic forearm exercise. *J Physiol*. 2006;570(pt 1):185–205. doi:10.1113/jphysiol.2005.094615
38. Swank A, Robertson RJ. Effect of induced alkalosis on perception of exertion during intermittent exercise. *J Appl Physiol*. 1989;67(5):1862–1867. doi:10.1152/jappl.1989.67.5.1862
39. Higgins MF, James RS, Price MJ. The effects of sodium bicarbonate (NaHCO3) ingestion on high intensity cycling capacity. *J Sports Sci*. 2013;31(9):972–981. doi:10.1080/02640414.2012.758868
40. Saunders B, Sale C, Harris RC, Sunderland C. Sodium bicarbonate and high-intensity-cycling capacity: variability in responses. *Int J Sports Physiol Perform*. 2014;9(4):627–632. doi:10.1123/ijspp.2013-0295
41. Hawley JA, Burke LM. Effect of meal frequency and timing on physical performance. *Br J Nutr*. 1997;77(suppl 1):S91–S103. doi:10.1079/bjn19970107
42. Gurton WH, Matta GG, Gough LA, Ranchordas MK, King DG, Hurst P. Sodium bicarbonate and time-to-exhaustion cycling performance: a retrospective analysis exploring the mediating role of expectation. *Sports Med—Open*. 2023;9(1):65. doi:10.1186/s40798-023-00612-5
43. Gurton WH, Greally J, Chudzikiewicz K, Gough LA, Lynn A, Ranchordas MK. Beneficial effects of oral and topical sodium bicarbonate during a battery of team sport-specific exercise tests in recreationally trained male athletes. *J Int Soc Sports Nutr*. 2023;20(1):2216678. doi:10.1080/15502783.2023.2216678
44. Gough LA, Newbury JW, Price M. The effects of sodium bicarbonate ingestion on swimming interval performance in trained competitive swimmers. *Eur J Appl Physiol*. 2023;123(8):1763–1771. doi:10.1007/s00421-023-05192-6
45. Gurton WH, King DG, Ranchordas MK, Siegler JC, Gough LA. Enhancing exercise performance and recovery through sodium bicarbonate supplementation: introducing the ingestion recovery framework. *Eur J Appl Physiol*. Published online August 23, 2024. doi:10.1007/s00421-024-05578-0