Effects of pre-exercise alkalosis on the decrease in V˙ O2 at the end of all-out exercise

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Claire Thomas[1,2] · Rémi Delfour-Peyrethon[1] · David J. Bishop[3] · Stéphane Perrey[4] · Pierre-Marie Leprêtre[5] · Sylvain Dorel[6] · Christine Hanon[1]

Abstract

Purpose This study determined the effects of pre-exercise sodium bicarbonate ingestion (ALK) on changes in oxygen uptake ($\dot{V}O_2$) at the end of a supramaximal exercise test (SXT).

Methods Eleven well-trained cyclists completed a 70-s all-out cycling effort, in double-blind trials, after oral ingestion of either 0.3 g kg^{-1} of sodium bicarbonate ($NaHCO_3$) or 0.2 g kg^{-1} body mass of calcium carbonate (PLA). Blood samples were taken to assess changes in acid–base balance before the start of the supramaximal exercise, and 0, 5 and 8 min after the exercise; ventilatory parameters were also measured at rest and during the SXT.

Results At the end of the PLA trial, which induced mild acidosis (blood pH = 7.20), subjects presented a significant decrease in $\dot{V}O_2$ ($P < 0.05$), which was related to the amplitude of the decrease in minute ventilation ($\dot{V}_E$) during the SXT ($r = 0.70$, $P < 0.01$, $n = 11$). Pre-exercise metabolic alkalosis significantly prevented the exercise-induced decrease in $\dot{V}O_2$ in eleven well-trained participants (PLA: 12.5 ± 2.1 % and ALK: 4.9 ± 0.9 %, $P < 0.05$) and the decrease in mean power output was significantly less pronounced in ALK ($P < 0.05$). Changes in the $\dot{V}O_2$ decrease between PLA and ALK trials were positively related to changes in the $\dot{V}_E$ decrease ($r = 0.74$, $P < 0.001$), but not to changes in power output ($P > 0.05$).

Conclusions Pre-exercise alkalosis counteracted the $\dot{V}O_2$ decrease related to mild acidosis, potentially as a result of changes in $\dot{V}_E$ and in muscle acid–base status during the all-out supramaximal exercise.

Keywords Oxygen uptake · Minute ventilation · Acid–base status · High-intensity exercise · Fatigue · Sodium bicarbonate

Abbreviations

ALK	Alkalosis trial due to pre-exercise sodium bicarbonate ingestion
BE	Base excess
Bf	Breathing frequency
$CaCO_3$	Calcium carbonate
FI	Fatigue index
H^+	Proton
HR	Heart rate
HR_{max}	Maximal HR
GXT	Graded exercise test
$[HCO_3^-]_b$	Blood bicarbonate concentration
$[La]_b$	Blood lactate concentration
MAP	Maximal aerobic power
$NaHCO_3$	Sodium bicarbonate

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Ptot	Mean power for the entire test
P20	Mean power during the first 20 s of the test
P50	Mean power during the last 50 s of the test
$P5_{end}$	Mean power during the last 5 s of the test
pΔ50	Power output midway between the MAP and the maximal theoretical power produced at the corresponding pedaling rate
$PETO_2$	End-tidal O_2 tension
$PETCO_2$	End-tidal CO_2 tension
PLA	Placebo trial due to pre-exercise calcium carbonate ingestion
P_{max}	Maximal power output
Post-Ing	60 min post-ingestion of the supplementation or placebo
Pre-Ex	Immediately before the 70-s supramaximal exercise
Post-Ex	Immediately after the 70-s supramaximal exercise
R5	5 min of the recovery after the supramaximal exercise test
R8	8 min of the recovery after the supramaximal exercise test
SaO_2	Arterial oxygen saturation
SXT	Supramaximal exercise test
$\dot{V}CO_2$	Carbon dioxide production
$\dot{V}_E$	Minute ventilation
$\dot{V}O_2$	Oxygen uptake
$\dot{V}O_{2\,max}$	Maximal oxygen uptake
$\dot{V}O_{2\,end}$	Oxygen uptake at the end of the test in the last 5 s
$\dot{V}_{E\,end}$	Minute ventilation at the end of the test in the last 5 s
$\dot{V}O_{2peak}$	Peak oxygen uptake
$\dot{V}_{E\,peak}$	Peak minute ventilation
V_T	Tidal volume

Introduction

Supramaximal exercise until exhaustion is characterized by a decline in muscle performance at the end of exercise (Fitts 1996), which has been associated with a decrease in oxygen uptake ($\dot{V}O_2$) (Thomas et al. 2005). This specific $\dot{V}O_2$ response pattern has been shown to occur at the end of both self-paced and constant power exercise performed until exhaustion, particularly in well-trained athletes (Nummela et al. 1992; González-Alonso and Calbet 2003; Thomas et al. 2005; Mortensen et al. 2008; Hanon et al. 2010; Jalab et al. 2011). The decrease in $\dot{V}O_2$ has been attributed to failure of the heart to maintain cardiac output and O_2 delivery to locomotive muscles (González-Alonso and Calbet 2003; Mortensen et al. 2008; Hanon et al. 2010), and also to the increase in blood proton and lactate concentration at the end of supramaximal running exercises (400-, 800-, 1500-m running races) (Hanon and Thomas 2011; Hanon et al. 2010).

The hypothesis that metabolic disturbances may contribute to the decrease in $\dot{V}O_2$ at the end of supramaximal exercises is in accordance with the relationship observed between blood pH and the $\dot{V}O_2$ response in the last 100 m of a 400-m running race (Hanon et al. 2010), and with the large decrease in blood bicarbonate concentration ($[HCO_3^-]_b$) after competitive rowing (Nielsen 1999). Both proton (H^+) and lactate accumulation have been reported to affect the excitation–contraction coupling process in skeletal muscle (Fitts 1996), and both the $\dot{V}O_2$ response and the decrease in velocity at the end of 400- and 800-m races has been related to high-metabolic disturbances (Hanon and Thomas 2011; Thomas et al. 2005; Hanon et al. 2010). Reducing muscle pH may also affect energy supply (Hirvonen et al. 1992) via established effects on glycolytic and oxidative enzymes (Gaitanos et al. 1993; Jubrias et al. 2003) and the rate of oxidative phosphorylation (Walsh et al. 2002; Jubrias et al. 2003).

Metabolic acidosis during high-intensity exercise could also induce physiological perturbations in the O_2 transport system by influencing ventilatory responses which have been linked to changes in acid–base balance (Lindinger and Heigenhauser 2012) and the affinity of oxygen to hemoglobin (Bohr et al. 1904). A strong positive relationship has been observed between ventilatory parameters (decrease in tidal volume) and the decrease in the $\dot{V}O_2$ during the last 100 m of 400-, 800- and 1500-m running races (Hanon et al. 2010), which could reflect a hyperpnoea due to metabolic acidosis (Forster and Pan 1995). The runners may have hyperventilated in order to partially compensate their metabolic acidosis and to maintain an effective alveolar O_2 pressure (Miyachi and Katayama 1999). All of these changes suggest that if the organism is unable to prevent additional acidosis, it may result in a complex series of metabolic effects during exercise that lead to a decrease in $\dot{V}O_2$ at the end of exhaustive supramaximal exercise.

A limitation of the above-mentioned research is that it has predominantly relied on correlations between pH changes and physiological modifications. A means to assess the effects of metabolic acidosis on the end-exercise decrease in $\dot{V}O_2$ would be to delay the accumulation of H^+ via the ingestion of a buffering agent [i.e., sodium bicarbonate ($NaHCO_3$) or sodium citrate taken 90–120 min before exercise] (Bishop et al. 2004). While pre-exercise metabolic alkalosis has controversial effects on performance improvement during high-intensity exercise, it has been reported to facilitate lactate and proton transport across the sarcolemmal membrane (Becker and Deitmer 2004; Kristensen et al. 2004), and to enhance energy supply via glycolytic (Hollidge-Horvat et al. 2000; Bishop et al. 2004)

and oxidative metabolic pathways (Hollidge-Horvat et al. 2000). Pre-exercise alkalosis has equivocal effects on pulmonary $\dot{V}O_2$ kinetics during heavy exercises (Nielsen et al. 2002; Kolkhorst et al. 2004; Zoladz et al. 2005; Berger et al. 2006), but could result in increased CO_2 release and consequently may be associated with changes in ventilatory regulation.

Therefore, the present research aimed to investigate the effects of altering extracellular pH on the end-exercise $\dot{V}O_2$ decrease during acute supramaximal exercise. Based on the aforementioned studies, it was hypothesised that pre-exercise alkalosis would prevent or reduce the $\dot{V}O_2$ decrease. In an attempt to verify this hypothesis, the oxygen uptake and performance responses of highly trained participants were measured during 70-s of supramaximal exercise performed under induced alkalosis or a placebo trial.

Methods

Participants

Eleven trained cyclists (10 males and 1 female: age 24.5 ± 2.8 years, height 1.78 ± 2.7 m and body mass 73.2 ± 3.8 kg) volunteered for this study. They had at least 5 years of cycling experience and trained 8 hours per week in sprint track-cycling and/or BMX. All subjects were successful at national-level events. None had a history of pathology of the lower-limb muscles or joints. They were informed of the nature of the study and the possible risks and discomforts associated with the experimental procedures before giving their written informed consent to participate. The experimental design of the study was approved by the French Ethical Committee of Saint-Germain-en-Laye (n°2009-A01004-53) and was carried out in accordance with the Declaration of Helsinki.

Experimental design

The testing sessions took place in a well-ventilated laboratory at a temperature of 20–22 °C. In addition to a familiarization session for all tests, the main experiment required the participants to be tested on three separate occasions within 2 weeks, with a minimum of 72 h between each test. All exercises were conducted using an electronically-braked cycle ergometer (Excalibur Sport, Lode, Groningen, The Netherlands). The vertical and horizontal positions of the saddle, handlebar height, crank and stem lengths were set to match the most comfortable and usual position of the participants. All exercise tests were performed in the standing position.

An initial laboratory visit was scheduled to obtain data on physical characteristics, and to enable familiarization with the cycle ergometer and the supramaximal exercise test. On day two, participants performed a torque–velocity test in order to determine their maximal power output (P_{max}), and a graded exercise test (GXT) to determine both their maximal $\dot{V}O_2$ ($\dot{V}O_{2max}$) and their maximal aerobic power (MAP). At least 72 h later, participants performed the 70-s supramaximal exercise test (SXT) 90 min after the ingestion of either $NaHCO_3$ or a placebo (calcium carbonate: $CaCO_3$). A week later, participants performed the alternate trial, and both SXT were conducted at the same time of day to control for diurnal effects. Participants were required to consume no food or beverages (other than water) 2 h before testing and were asked not to consume alcohol or perform vigorous exercise in the 24 h before testing.

Substance ingestion

Participants ingested either 0.3 g kg^{-1} of $NaHCO_3$ (Alkalosis trial: ALK) or 0.2 g kg^{-1} of $CaCO_3$ (Placebo trial: PLA), contained within 1-g gelatin capsules, with 500 mL of water 90 min before performing the SXT. Trial was assigned in a counterbalanced, randomized, double-blind manner.

First test session

Torque–velocity test

Participants began with a 20-min warm-up consisting of 15 min of cycling at 100-150 W followed by a 5-s sprint. The participants were then asked to perform three maximal cycling sprints (5 s in duration with 8 min of total recovery) according to the protocol proposed by Dorel et al. (Dorel et al. 2010). Three different resistive torques of 0, 0.7–1, 1.4–1.8 Nm kg^{-1} body mass were applied to obtain maximal force and power values from a large range of pedaling rates during the three bouts. After computation, the cumulated data from the three sprints were used to draw force–velocity and power–velocity relationships and hence to determine maximum power (P_{max}) and the corresponding specific optimal pedaling rate at which P_{max} occurred (for details, see Dorel et al. 2010).

Assessment of maximal oxygen uptake and maximal aerobic power (MAP)

After 20 min of rest, participants performed a graded exercise test to determine their $\dot{V}O_{2max}$ and their MAP (i.e., the power output achieved when $\dot{V}O_{2max}$ was first reached). The progressive protocol consisted of 6 min of pedaling at 100 W followed by a ramp increase in power output of 20 W min^{-1} until voluntary exhaustion. Participants

were instructed to maintain their chosen preferred cadence as long as possible and the test was completed when the cadence decreased more than 10 rpm below this value for more than 5 s despite strong verbal encouragement. All ventilatory parameters and heart rate (HR) values were recorded continuously during the test.

Second and third test sessions

70-s supramaximal exercise tests

During the 3rd and 4th visits, participants performed supramaximal exercise tests in one of the two trials of supplementation (ALK or PLA). One hour after the beginning of the supplementation, they performed a standardized warm-up consisting of 8 min at 150 W, 2 min at 260 W, a recovery period (2 min of rest), a 10-s sprint of progressively increasing intensity with the last 3 s performed at maximal intensity, 90 s of recovery, and fi two brief 5-s sprints interspersed with 90 s of recovery. Upon completion of the warm-up, participants rested for 10 min before performing the SXT. Before starting the 70-s test, participants were asked to assume the ready position and await the start signal. The initial work rate (pΔ50) was held constant during the fi 20 s to avoid differences in pacing strategies between the two tests. Participants were then asked to maintain their pedaling rate (isokinetic mode) at 90 rpm. The power pΔ50 was defi as the power output midway between the MAP and the maximal theoretical power produced at the corresponding pedaling rate (determined from the torque–velocity test). After this initial 20-s period, subjects were asked to perform an all-out maximal effort in isokinetic mode until the end of the test. Strong verbal encouragement was provided to each subject during all SXT, but no feedback on test duration was given to the participants.

Material and data collection/processing

Performance

During the SXT, different mechanical power outputs (W) were calculated: the mean power for the entire test (Ptot), during the first 20 s (P20), during the last 50 s (P50) and during the last 5 s ($P5_{end}$). A fatigue index (FI) was calculated as: ($P5_{end}$-P20)/P20 and expressed as a percentage.

Cardio-respiratory parameters

During both sessions (GXT and SXT), breath-by-breath $\dot{V}O_2$, minute ventilation ($\dot{V}_E$), carbon dioxide production ($\dot{V}CO_2$), breathing frequency (Bf), tidal volume (V_T), and end-tidal O_2 and CO_2 tensions ($PETO_2$ and $PETCO_2$) were recorded continuously with a laboratory metabolic cart (Quark CPET, Cosmed, Roma, Italy). Calibration of the gas analyser was performed according to the manufacturer's instructions before each test for each subject. The different ventilatory variables were recorded continuously during the entire experimental protocol. For the GXT, breath-by-breath gas exchange values were smoothed (i.e., 3-s moving average). The highest $\dot{V}O_2$ value in a 30-s period was considered as the $\dot{V}O_{2max}$. The criteria used for the determination of $\dot{V}O_{2max}$ were threefold: a plateau in $\dot{V}O_2$ despite an increase in power output, a respiratory exchange ratio above 1.1 and a HR above 90 % of the predicted maximal HR (HR_{max}) (Howley et al. 1995). To determine peak $\dot{V}O_2$ ($\dot{V}O_{2peak}$) and peak $\dot{V}_E$ ($\dot{V}_{Epeak}$) during the supramaximal exercise tests, breath-by-breath values were smoothed (i.e. 3-s central moving average) and then a 5-s average was applied in order to compare $\dot{V}O_2$ and other ventilatory responses ($\dot{V}CO_2$, V_T, Bf, $\dot{V}_E$, $PETO_2$). Using the same methods, end $\dot{V}O_2$ ($\dot{V}O_{2end}$) and end $\dot{V}_E$ ($\dot{V}_{Eend}$) were determined in the last 5 s of the SXT. Changes in ventilatory parameters were calculated by [(peak value − end value)/peak value × 100]. The $\dot{V}O_2$ decrease phenomenon was considered to have occurred when the magnitude of the phenomenon was both larger than both 5 % (Billat et al. 2009) and 5 ml of the peak value during an interval of time of at least 15 s, while the subject continued to cycle at or above MAP (Hanon et al. 2013). HR was measured and recorded continuously with a heart rate monitor (S810i and T61 electrode belt, Polar Electro, Kempele, Finland) for each subject. Finally, blood oxygen saturation (SpO_2) was measured by pulse oximetry with a digital probe (Cosmed, Roma, Italy).

Capillary blood sampling and analysis

At rest, after the warm-up of the torque–velocity protocol, and at exhaustion, 5 and 8 min after the GXT, 5-µL capillary blood was collected from the earlobe and blood lactate concentration ($[La]_b$) was determined with a Lactate Pro analyser (Arkray, Japan). Before and after the SXT session, 85 µL capillary blood samples were analyzed to measure blood pH, arterial oxygen saturation (SaO_2), base excess (BE) and $[HCO_3^-]_b$ with an i-STAT dry chemistry analyser (Abbott, Les Ulis, France). Capillary blood was sampled 60 min post-ingestion of the test substance, 90 min post-ingestion (i.e., after the end of the warm-up, immediately pre-exercise), and immediately after the SXT, and after 5 and 8 min of recovery. Measurements with the i-STAT portable analyser, anaerobically collected (cartridges closed hermetically), have been found to be reliable (ICC = 0.77–0.95) following maximal exercise (Dascombe et al. 2007).

Statistical analysis

Descriptive statistics are expressed as mean ± SE. The level of significance was set at $P < 0.05$. Differences in

PLA and ALK were identified by means of the paired student *t* test or Wilcoxon signed rank test depending on the normality. One-way ANOVA (1 group × 2 trials), with repeated measures for trial, were used to compare ventilatory, blood and performance data. Where appropriate, post hoc comparisons were employed (Student–Newman–Keuls test). Relationships between variables were analyzed by a Pearson's correlation coefficient. All statistical analyses were conducted using Sigmastat software (version 3.1).

Results

Graded exercise test

$\dot{V}O_{2max}$ during the graded exercise test was equal to 3.98 ± 0.21 L.min^{-1} and MAP corresponded to 334.5 ± 17.7 W. Maximal mean values of $\dot{V}_E$, Bf and V_T were 152.5 ± 8.8 L min^{-1}, 54.7 ± 2.0 cycles min^{-1}, and 2.8 ± 0.1 L, respectively. Mean values of HR_{max} corresponded to 189 ± 4 beats min^{-1}.

Supramaximal exercise tests

Blood gas variables

As shown in Fig. 1, the ingestion of $NaHCO_3$ produced the expected effects on blood acid–base status, and $[HCO_3^-]_b$, blood pH and BE were significantly elevated 60 min post-ingestion and immediately before the SXT ($P < 0.05$). Following the warm-up, there were significant decreases in blood $[HCO_3^-]_b$, BE and $[La]_b$ in both trials ($P < 0.05$). Blood pH, $[HCO_3^-]_b$, and BE significantly decreased after the SXT in both trials, but blood pH and BE were significantly higher in the ALK trial at 0, 5 and 8 min during the recovery compared to the PLA trial ($P < 0.05$). After SXT, $[La]_b$ significantly increased, but no significant difference was observed for $[La]_b$ between trials ($P > 0.05$). Arterial saturation significantly decreased in the PLA or ALK trials

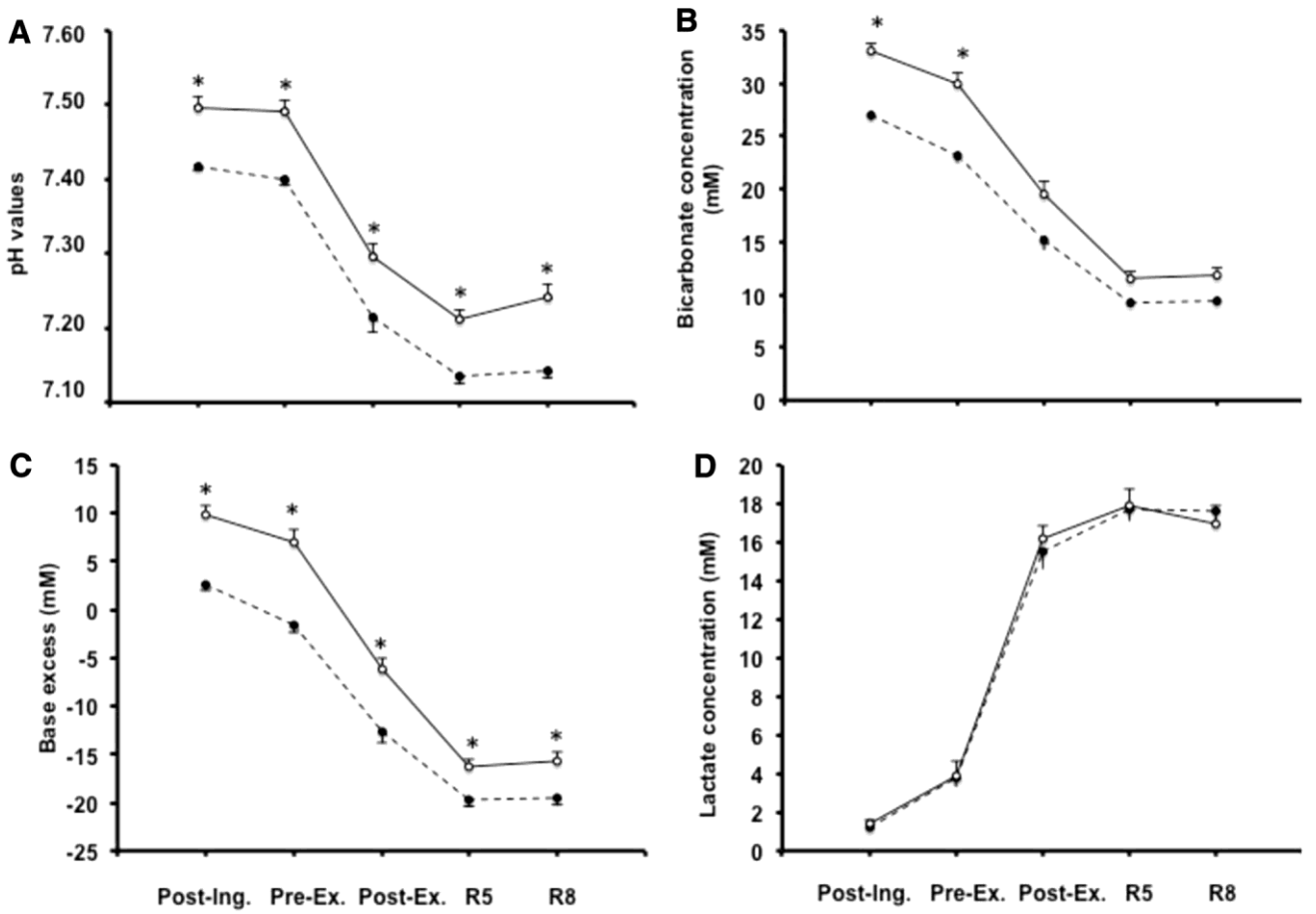

Fig. 1 Blood pH (**a**), $[HCO_3^-]$ (**b**), base excess (**c**), and (lactate) (**d**) responses following ingestion of either a placebo (PLA: *black*) or sodium bicarbonate (ALK: *white*), 60 min post-ingestion (Post-Ing), immediately after the warm-up and before the supramaximal exercise (Pre-Ex), immediately after the 70-s supramaximal exercise (Post-Ex) and after 5 (R5) and 8 (R8) min of recovery following the supramaximal exercise test. $n = 11$ for PLA and $n = 11$ for ALK. * $P < 0.05$ significant difference between ALK and PLA

during the SXT (Table 1, $P < 0.05$), and was significantly higher in the ALK trial at the end of the SXT ($P < 0.05$).

$\dot{V}O_2$, $\dot{V}CO_2$ and ventilatory responses

As shown in Fig. 2, oxygen uptake increased to a steady state corresponding to 97.2 ± 2.6 (PLA) and 96.5 ± 3.1 (ALK) % of $\dot{V}O_{2max}$, with no significant difference between trials ($P > 0.05$). Towards the end of the SXT (Table 1), $\dot{V}O_2$ decreased by 12.5 ± 2.1 % in PLA ($P < 0.01$), which was prevented by pre-exercise alkalosis (4.9 ± 0.9 % in ALK, $P < 0.05$). Furthermore, $\dot{V}O_{2end}$ was significantly lower than $\dot{V}O_{2max}$ in the both trial ($P < 0.05$),

Table 1 Group mean (± SE) physiological responses to the 70-s all-out test after PLA and ALK supplementations

	PLA	ALK
$\dot{V}O_{2peak}$ (L min^{-1})	3.87 ± 0.23	3.88 ± 0.27
$\dot{V}O_{2end}$ (L min^{-1})	3.38 ± 0.21$^{\$}$	3.68 ± 0.24$^{\$}$
Difference$_{between\ peak\ and\ end\ values\ for\ \dot{V}O_2}$ (%)	12.5 ± 2.1	4.9 ± 0.9*
$\dot{V}CO_{2peak}$ (L min^{-1})	5.3 ± 0.3	5.9 ± 0.4*
$\dot{V}CO_{2end}$ (L min^{-1})	5.0 ± 0.3$^{\$}$	5.7 ± 0.4$^{\$,*}$
Difference$_{between\ peak\ and\ end\ values\ for\ \dot{V}O_2}$ (%)	4.7 ± 1.4	4.3 ± 1.5
$\dot{V}_{Epeak}$ (L min^{-1})	168.9 ± 9.0	171.0 ± 10.6
$\dot{V}_{Eend}$ (L min^{-1})	154.5 ± 8.6$^{\$}$	164.3 ± 10.0$^{\$}$
Difference$_{between\ peak\ and\ end\ values\ for\ \dot{V}E}$ (%)	8.4 ± 1.7	3.8 ± 0.8*
$PETO_2$	119.2 ± 1.3	118.3 ± 1.0
$PETCO_2$	38.9 ± 1.1	42.0 ± 0.9*
Arterial saturation at $t = 0$ s (%)	98.2 ± 0.2	98.5 ± 0.3
Arterial saturation at $t = 70$ s (%)	94.9 ± 1.3$^{£}$	96.9 ± 0.8$^{*,£}$
P20 (W)	813.7 ± 46.6	831.2 ± 48.1
P50 (W)	448.2 ± 27.7	469.6 ± 28.6*
Ptot (W)	549.5 ± 29.1	564.5 ± 29.5*
Fatigue index (%)	59.8 ± 2.3	61.4 ± 2.9

Arterial saturation values determined at the beginning ($t = 0$ s) and at the end of exercise ($t = 70$ s)

$n = 11$

PLA group with placebo supplementation, *ALK* group with sodium bicarbonate supplementation, $\dot{V}O_{2peak}$ *and* $\dot{V}O_{2end}$ peak and end values of pulmonary oxygen uptake, $\dot{V}CO_{2peak}$ *and* $\dot{V}CO_{2end}$ peak and end values of expired carbon dioxide, $\dot{V}_{Epeak}$ *and* $\dot{V}_{Eend}$ peak and end values of pulmonary ventilation, $PETO_2$ *and* $PETCO_2$ end-tidal partial pressure of O_2 and CO_2 during the last 20 s of the test, *P20* mean power output during the first 20 s of the test, *P50* mean power output during the last 50 s of the test, *Ptot* mean power output during the whole 70 s of the test, *NS* no significant difference

* $P < 0.05$ Significant difference between PLA and ALK

$^{\$}$ $P < 0.05$ Significant difference from peak value

$^{£}$ $P < 0.05$ Significant difference from $t = 0$ s

whereas the power output at the end of the SXT was not significantly different from MAP ($P > 0.05$).

As shown in Table 1, a signifi decrease in $\dot{V}_E$ was also observed at the end of the SXT in both trials (PLA: 8.4 ± 1.7 %, $P < 0.01$, and ALK: 3.8 ± 0.8 %, $P < 0.05$). The decrease was signifi less pronounced in the ALK ($P < 0.05$) compared to the PLA trial. As shown in Fig. 3, the decrease in $\dot{V}O_2$ was signifi related to this decrease in $\dot{V}_E$ in all subjects ($r = 0.70$, $P < 0.01$, $n = 11$). The changes in the $\dot{V}O_2$ decrease between the PLA and ALK trials was highly correlated to the change in the $\dot{V}_E$ decrease ($r = 0.74$, $P < 0.001$, $n = 11$). Furthermore, both $\dot{V}CO_{2peak}$ and $\dot{V}CO_{2end}$ were signifi higher in the ALK trial compared to the PLA trial, but $\dot{V}CO_2$ decreased until the end of the SXT in both trials ($P < 0.05$) with the same magnitude ($P > 0.05$). Finally, during the last 20 s of the SXT, $PETO_2$ was similar in both trials ($P > 0.05$), whereas $PETCO_2$ ($P < 0.001$) was signifi higher in the ALK trial compared to the PLA trial.

Mechanical performance

The values for P20, P50, $P5_{end}$ and Ptot of the SXT are given in Table 1. During the fi 20 s of the SXT, the mean power output was not signifi different between trials ($P > 0.05$). As shown in Fig. 4, this parameter signifi decreased for both trials ($P < 0.001$), and signifi higher values were observed for P50 and Ptot in the ALK trial ($P < 0.05$) compared to the PLA trial. Indeed, the signifi differences in power output between both trials were between the 20th and 45th seconds of the test. Furthermore, the $\dot{V}O_2$ decrease was not related to the decrease in power-output in the last 50 s in both trials ($P > 0.05$), and the difference in power output between ALK and PLA was not related to the difference in $\dot{V}O_2$ decrease ($P > 0.05$).

Discussion

In the present study, the participants presented a significant $\dot{V}O_2$ decrease in the placebo trial at the end of the supramaximal cycling exercise. The result was that raising the blood pH before and during the supramaximal exercise task via pre-exercise ingestion of $NaHCO_3$, significantly reduced the $\dot{V}O_2$ decrease in these well-trained participants. The decrease in $\dot{V}O_2$ in both trials was related to the amplitude of the $\dot{V}_E$ decrease, and the difference in the $\dot{V}O_2$ decrease between the PLA and ALK trials was positively correlated with the difference in the $\dot{V}_E$ decrease. The $\dot{V}O_2$ decrease was not associated with the changes in power output in either trial.

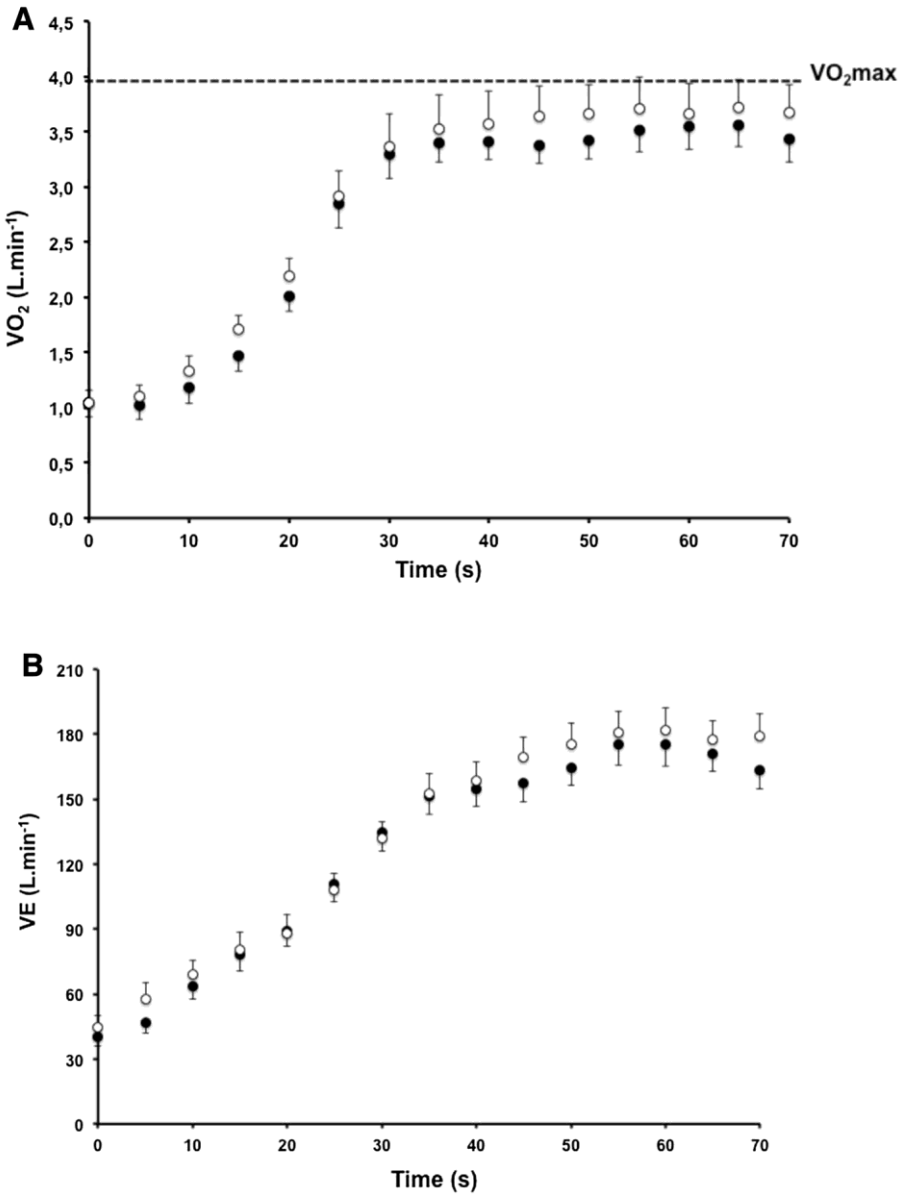

Fig. 2 Mean ± SE ventilatory and gas exchange responses during the 70-s supramaximal exercise test after supplementation of placebo (PLA: *black*) and sodium bicarbonate (ALK: *white*) prior to the supramaximal exercise. $\dot{V}O_2$max: maximal oxygen uptake. $n = 11$ for PLA and $n = 11$ for ALK

$\dot{V}O_2$ decrease and blood acidosis

A mean $\dot{V}O_2$ decrease of 12.5 % was observed at the end of the 70-s supramaximal exercise test for participants in the PLA trial (Fig. 2), which confirmed previous data obtained at the end of exhaustive running (Perrey et al. 2002; Thomas et al. 2005; Hanon et al. 2010), cycling (Astrand and Saltin 1961; González-Alonso and Calbet 2003; Mortensen et al. 2008) and swimming (Jalab et al. 2011) exercises. Given the short-duration smoothing and averaging bins that were used (3 and 5 s, respectively), the influence of breath-to-breath variability has been considered. Consequently, the criteria of a magnitude larger than both 5 % (Billat et al. 2009) and 5 mL were used to characterize a $\dot{V}O_2$ decrease during the last 15 s of the test and to be confident there was a physiologically relevant decrease in $\dot{V}O_2$ as opposed to stochastic or even non-stochastic noise. To confirm the reproducibility of data analysis with this sampling window, one can note that subjects have the same peak values for $\dot{V}O_2$, and $\dot{V}_E$ in both trials ($P > 0.05$), and that the kinetics of blood lactate were similar after both SXTs ($P > 0.05$), reflecting indirectly the same metabolic demand.

In order to test the hypothesis that pre-exercise alkalosis could reduce the magnitude of this phenomenon, we used a loading dose of 0.3 kg^{-1} body mass of $NaHCO_3$ in our experimental design. As expected (Hollidge-Horvat et al. 2000; Bishop et al. 2004), this resulted in significant alterations of blood pH, $[HCO_3^-]_b$ and BE before the supramaximal test (Fig. 1), compared to the PLA trial. The

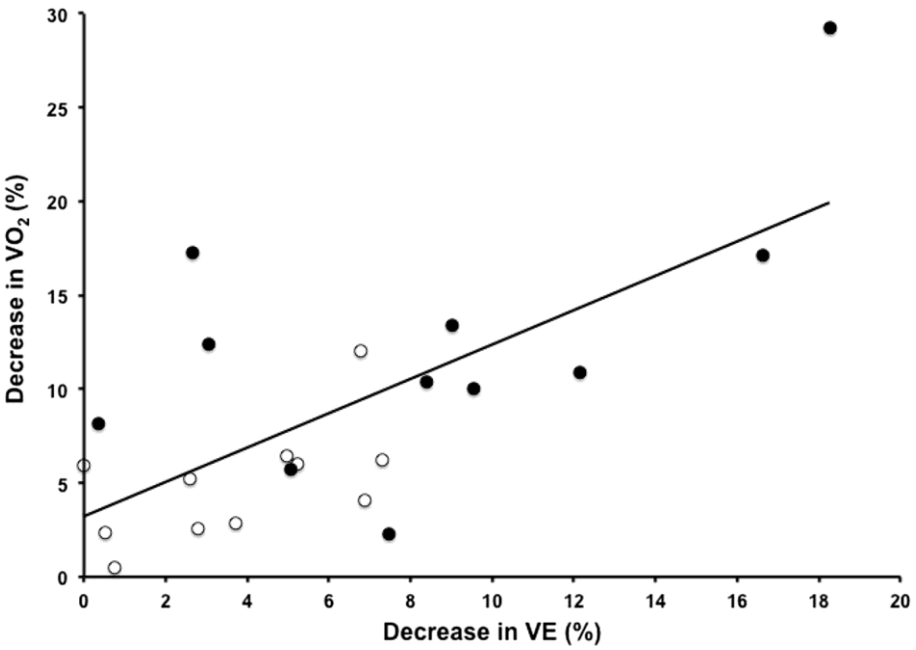

Fig. 3 Relationships between $\dot{V}_E$ decrease and $\dot{V}O_2$ decrease ($r = 0.70$, $P < 0.01$, $n = 11$ subjects), after supplementation of placebo (PLA: *black*) and sodium bicarbonate (ALK: *white*) prior supramaximal exercise

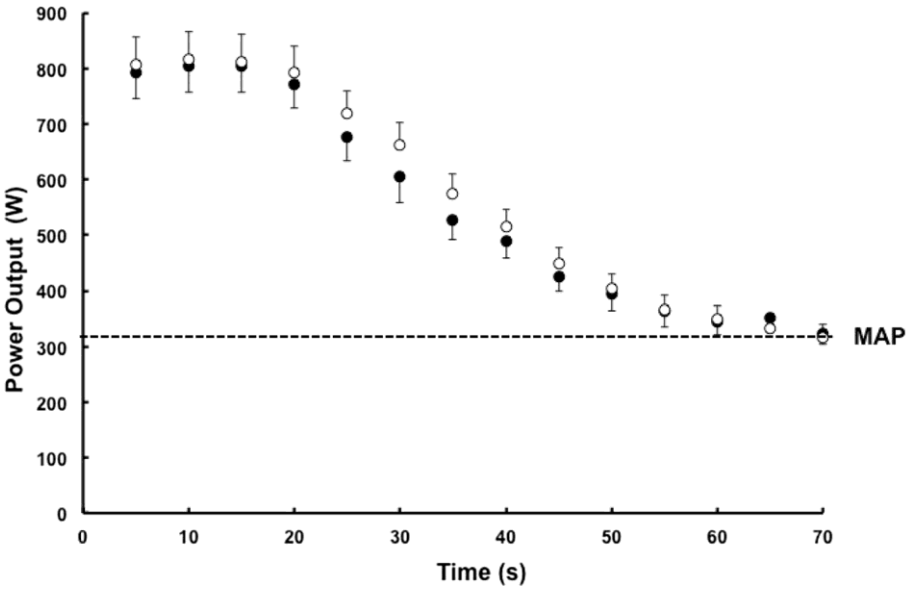

Fig. 4 Mean ± SE power output during the 70-s supramaximal test after supplementation of placebo (PLA: *black*) and sodium bicarbonate (ALK: *white*). $n = 11$ for PLA and $n = 11$ for ALK. *MAP* maximal aerobic power output

effect of pre-exercise-induced alkalosis was in accordance with our hypothesis since the $\dot{V}O_2$ decrease was significantly modified from 12.5 ± 2.1 % in PLA to 4.9 ± 0.9 in ALK ($P < 0.05$). This result is in line with the relationship observed between $\dot{V}O_{2end}$ values at the end of a 400-m race and acid–base status measured at 300 m of the race (Hanon et al. 2010). This suggests that higher blood pH values due to either pre-exercise alkalosis (present study) or a greater use of aerobic energy resources (present study and Hanon et al. 2010) could influence $\dot{V}O_2$ kinetics at the end of a supramaximal exercise task performed until exhaustion.

Decrease in $\dot{V}O_2$ and decrease in oxygen transport

Our results indicated that the $\dot{V}O_2$ decrease was related to the $\dot{V}_E$ decrease at the end of the SXT ($r = 0.70$, $P < 0.01$, $n = 11$, Fig. 3), and that pre-exercise ingestion of $NaHCO_3$ was associated with a larger $V_{E_{end}}$ and a smaller end-exercise decrease in $\dot{V}_E$ (Table 1); ALK did not have a significant effect on the $\dot{V}_{E\ peak}$ during the SXT (PLA: 168.9 ± 9.0 versus ALK: 171.0 ± 10.6 $L.min^{-1}$ for $\dot{V}_{E\ peak}$, $P > 0.05$). This is in accordance with data of Nielsen et al. (2002), suggesting that the peak ventilatory response to maximal cycling exercise was not attenuated by excess

H^+ concentration. Furthermore, the significant difference in $PETCO_2$ at the end of SXT between both trials (Table 1) is in favor of metabolic alkalosis allowing buffering of protons accumulation and stimulating chemoreceptor to counteract the decrease in $\dot{V}_E$. This also likely contributed to explain the significantly higher $\dot{V}CO_2$ value at the end of ALK SXT (Peronnet and Aguilaniu 2006) and confirmed the mathematical model of Duffin (Duffin 2005) which proposed a change in the chemoreflex threshold for PCO_2 with alkalosis. All these results could also be explained by a reduction of the dead space ventilation with change in arterial O_2 partial pressure with alkalosis (Nielsen et al. 2002). Related to this arterial desaturation could contribute to this phenomenon. Indeed, it has been suggested that $\dot{V}O_2$ could decrease by 2 % for each 1 % decrease in SaO_2 at least when arterial desaturation exceeds 95 % (Harms et al. 2000). In the present study, subjects presented an exercise-induced arterial hypoxemia (94.9 ± 1.3 %), which was counteracted in the ALK trial (96.9 ± 0.8 %, $P < 0.05$). This result leads us to conclude that this phenomenon may also contribute to the $\dot{V}O_2$ decrease at the end of the SXT in the PLA trial. Then, changes of several factors involved in ventilatory response and oxygen transport in response to ALK contribute to explain the $\dot{V}O_2$ decrease at the end of the SXT, when the blood acid–base status was altered.

Decrease in $\dot{V}O_2$ and performance

In the present study, a decrease in mean power output during the last 50 s in the PLA trial was measured, with a less pronounced decrease in power output in the ALK trial. However, we did not observe a relationship between the $\dot{V}O_2$ decrease and the change in power output during the SXT in the PLA trial, which was in accordance with previous results performed at a constant power output (Perrey et al. 2002; González-Alonso and Calbet 2003; Mortensen et al. 2008; Hanon et al. 2013) and a self-paced exhaustive trial (Hanon et al. 2010). Furthermore, the smaller decrease in $\dot{V}O_2$ in the ALK trial could not be explained by a higher initial power output with metabolic alkalosis. Indeed, we specifically chose to maintain the power output at a high constant level during the first 20 s in order to avoid a faster all-out start during ALK that would influence oxygen uptake and exercise tolerance (Jones et al. 2008).

One might suggest that the $\dot{V}O_2$ decrease could also be explained by an inability to generate more power in the PLA trial. However, the power output at the end of the SXT during the last 15 s in both trials was not significantly lower than the maximal aerobic power, which rebuts this hypothesis. This is in accordance with previous studies which also support the notion that the decrease in $\dot{V}O_2$ could appears when a constant power output is maintained prior to exhaustion (González-Alonso and Calbet 2003) or when the end velocity was higher than the maximal aerobic power (Hanon et al. 2010; Hanon et al. 2008; Thomas et al. 2005).

Decrease in $\dot{V}O_2$ and intracellular acidosis

This decrease in $\dot{V}O_2$ could also be related to the inhibition of oxidative phosphorylation induced by acidosis in the contracting muscles (Jubrias et al. 2003). Indeed, it has been reported that muscle acidosis could decrease the effectiveness of the signals driving oxidative phosphorylation (OXPHOS) (Forbes et al. 2005), and that a muscle pH of 6.6 produced a lower oxidative fl compared to a pH of 7.0 at a constant submaximal ADP concentration (Walsh et al. 2002). Although untested in the present study, these cellular effects induced by acidosis could also contribute to explain the greater decrease in $\dot{V}O_2$ at the end of exercise in the PLA trial when blood pH values were around 7.10, compared to the ALK trial when post-exercise pH values were ~7.21. Pre-exercise alkalosis has previously been reported to reduce the pH decrease in skeletal muscle (Stephens et al. 2002) and to affect ion regulation (Street et al. 2005), and, as acidosis has been reported to affect OXPHOS (Forbes et al. 2005), this could help to explain why subjects had higher $\dot{V}O_{2end}$ values in the ALK trial. In addition, pre-exercise alkalosis has been reported to induce higher glycolytic and oxidative pathways in skeletal muscle compared to placebo trial (Hollidge-Horvat et al. 2000). This could also explain the signifi less-pronounced $\dot{V}O_2$ decrease with pre-exercise alkalosis.

Decrease in $\dot{V}O_2$ and subjects responses

Whereas both ventilatory parameters and power output were affected by an alteration in blood pH, 2/11 participants were non-responders to pre-exercise alkalosis for changes in both $\dot{V}O_2$ and performance. It is important to clarify that they have the same ventilatory response and that they performed the same power output during the SXT in both trial. It is conceivable that the limited effects of alkalosis in these two participants could result from the small difference in their resting pH values (pH difference between ALK and PLA of 0.06) after supplementation between both trials compared to the other participants (pH difference between ALK and PLA of 0.10). This divergence could also be due to the fact that the capacity of fixed physicochemical buffers in the blood varies and that ventilatory compensation of metabolic acidosis also varies (Peronnet and Aguilaniu 2006). Then, these non-responder participants could explain why in some experiments pre-exercise alkalosis altered muscle fatigue and performance (Higgins et al. 2013), whereas in other studies it does not (Saunders et al. 2013).

Conclusion

In conclusion, even though the end-exercise $\dot{V}O_2$ decrease is likely to be the consequence of several factors induced by high-intensity exercise, the results of the present study demonstrate that a $\dot{V}O_2$ decrease occurs in both placebo and the pre-exercise alkalosis trials at the end of a 70-s supramaximal exercise test. However, pre-exercise alkalosis is able to reduce this decrease in most participants. This appears to be due to changes in the $\dot{V}_E$ decrease as a consequence of changes in the extracellular pH, but not to changes in performance.

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Compliance with ethical standards

Conflict of interest The authors declare no conflicts of interest, financial or otherwise.

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