SODIUM BICARBONATE AND SODIUM CITRATE: ERGOGENIC AIDS?

BERNARDO REQUENA, MIKEL ZABALA, PAULINO PADIAL, AND BELEN FERICHE

Department of Physical Education and Sport, University of Granada, Spain.

ABSTRACT. Requena, B., M. Zabala, P. Padial, and B. Feriche. Sodium bicarbonate and sodium citrate: Ergogenic aids? J. Strength Cond. Res. 19(1):213–224. 2005.—Numerous studies have used exogenous administration of sodium bicarbonate (NaHCO₃) and sodium citrate (Na-citrate) in an attempt to enhance human performance. After ingestion of NaHCO₃ and Na-citrate, two observations have been made: (a) There was great individual variability in the ergogenic benefit reached, which can be attributed to the level of physical conditioning of the subjects and to their tolerance of the buffer substance; and (b) the subjects who had ingested NaHCO₃ and Na-citrate showed higher levels of pH, bicarbonate, and lactate ion concentrations in their exercising blood than did the subjects who had ingested the placebo. A majority of the studies have suggested that the ingestion of both substances provides an ergogenic effect due to the establishment and maintenance of an elevated pH level during exercise. However, the exact mechanism by which the ergogenic effects occur has not been demonstrated conclusively. Sodium bicarbonate and Na-citrate seem to be effective in activities with a sufficient duration to generate a difference in the hydrogen ion gradient, characterized by a very high intensity and involving large muscular groups. However, in activities of equally high intensity, but with longer duration, the results obtained have been conflicting and inconclusive.

Key Words. induced alkalosis, buffer, pH, performance

INTRODUCTION

During high-intensity exercise, energy needs are mainly provided by anaerobic glycolysis. This is associated with a high level of lactic acid production, its dissociation into hydrogen ions (H⁺) and lactate ions (Lac⁻), within physiologic pH ranges (28), and a concomitant fall in blood and muscle pH (12, 45, 46). Decreases in pH (rising [H⁺]) produce fatigue (16, 60, 61), defined as a decrease in force production (34) in the presence of increased perception of effort (16, 98, 99). The increase in [H⁺] produces, among other reactions, an inhibition of calcium release from the sarcoplasmic reticulum (14, 15) and an inhibition of the interaction between actin and myosin (6, 17). In addition, changes in pH have been shown to have an effect on energy-producing capability (14, 97). A number of pH-sensitive enzymes (48, 97) can produce a decrease in the rate of glycolysis and a reduction in the rate of adenosine triphosphate (ATP) production during periods of high acidity. However, during this type of exercise the muscle has defense mechanisms which attempt to keep pH within acceptable rates. Fundamentally, these consist of minimizing the accumulation of free H⁺ through the intracellular buffer and favoring the movement of ions between the cell and the extracellular fluid (7, 96). The administration of alkalinizing agents has been suggested to delay the onset of fatigue during high-intensity exercise by slowing the decline in muscle pH (39, 40, 42, 63, 89). In this respect, numerous studies have examined the exogenous administration of alkalotic agents in an attempt to enhance human performance (see Table 1). However, the results of previous studies show considerable discrepancies. Studies both support and refute the efficacy of alkalotic agents as a way to enhance sport performance. This controversy could be the reason for the low popularity of these substances among athletes; quite the opposite has been observed for other widely accepted ergogenic aids (i.e., caffeine or creatine). Regarding the alkalinizing substances used, those which have been studied most extensively and to which we dedicate this review are sodium bicarbonate (NaHCO₃) and sodium citrate (Na-citrate).

The main object of this review is to critically examine the most relevant studies on the use of NaHCO₃ and Na-citrate as ergogenic aids, seeking to (a) describe the biochemical mechanism of both substances acting on muscle buffer mechanisms; (b) examine the methods and conclusions suggested by the researchers who have used NaHCO₃ and/or Na-citrate as ergogenic aids in humans; and (c) determine the applicability of oral ingestion or intravenous infusion of these substances, used with the purpose of improving sport performance.

SODIUM BICARBONATE

Acting Mechanism

The exogenous intake of NaHCO₃ from 1 to 3 hours before exercise results in an important increase in the pH and bicarbonate (HCO₃⁻) concentrations in blood at the beginning of an exercise session, as well as during and after it (Figure 1) (12, 25, 64, 71, 76, 86, 90, 99, 103), whereas intramuscular pH and [HCO₃⁻] remain apparently unchanged (39, 71, 73). In some of the studies, it has been shown that the cellular membrane is essentially impermeable to HCO₃⁻, and therefore its action on intracellular pH seems to be indirect (14, 38, 49, 97). In this respect, the mechanism by which the intake of NaHCO₃ may enhance performance seems to be due to the increase in the buffering capacity of the extracellular medium (30, 66). Various studies (4, 38, 40, 47, 61, 89) have confirmed that increased extracellular pH and higher [HCO₃⁻] raise the H⁺ and Lac⁻ efflux from active muscles. This is due to an increase in the activity of the Lac⁻/H⁺ cotransporter, which becomes more active as the intracellular/extracellular H⁺ gradient increases, during contraction as well as during recovery (88). It has been suggested that this mechanism causes a decrease in muscular fatigue, delaying the decrease in pH level (64) and leading to a greater contractile capacity of the muscular tissue involved (66, 71, 76), by means of enhanced muscle glycolytic ATP production (4, 48, 97). It has been proven that all of these
metabolic perturbations imply a shift in muscle metabolism toward anaerobic energy production (19, 96), which is especially advantageous during high-intensity exercise (39, 70).

Main Research Carried Out Involving NaHCO₃

Sodium bicarbonate is the most frequently used alkalotic agent, and researchers have studied its effects on different types of activities, such as sprinting (29, 41, 42, 106), cycling (46, 50, 69, 70, 71, 75, 78, 79), interval swimming (26, 82), and rowing (72); and in populations pertaining to different sporting activities (5, 12, 29, 43, 80, 105).

Main Results Obtained in High-Intensity Short-Term Exercise (Less Than 120 Seconds). Conflciting results have been reported when testing an exercise duration of less than 2 minutes. Goldfinch et al. (29) found that in the alkalotic condition, 400-m runners ran significantly faster (1.52 seconds) than in the placebo condition. Similar results have been shown for 800-m race times (106). McNaughton et al. (68, 76, 78) recorded significant improvement in total work (i.e., 21.11 vs. 24.12 kJ in 60 seconds, p < 0.05) and in peak power (i.e., 706.0 vs. 779.6 W in 60 seconds, p < 0.05) performed on a cycle ergometer by means of maximum effort with a duration of 60–90 seconds. These studies suggested that NaHCO₃ ingestion facilitates efflux of H⁺ from the working tissues, thus decreasing intracellular pH and offsetting fatigue.

However, even though many of the studies have shown that NaHCO₃ administration modifies the blood acid-base balance, its effects on performance are not always positive (41, 43, 64, 82, 100). For instance, no improvements have been registered in the time required to run 600 m (100), 2-minute sprints (41), in work performed and peak power achieved during a Wingate test (30 seconds) (43), or following 90 seconds of maximal cycle exercise by untrained men (64). The lack of effect of NaHCO₃ administration upon performance in these types of exercise durations could be related to methodological considerations: (a) the small number of the sample (42), (b) the characteristics of subjects participating (100), (c) the small NaHCO₃ doses used (41), (d) the selection of an insufficient duration (43) and/or intensity of exercise that could result in insignificant differences in intramuscular pH (64), and (e) the variability in the environmental conditions in the field setting.

Main Results Obtained in Repeated Bouts Protocols. The use of NaHCO₃ during repeated sprint protocols also proved to be effective in some studies (12, 26, 30, 56, 67, 78), but not others (1, 13, 24, 55, 81, 82). Performance enhancement has been observed when repeating 10 times 6 seconds of running (24) and 10 times 10 seconds of cycling (56) at maximum intensity (see Table 1). Extending this line of research, Gao et al. (26) registered in a sample of swimmers an improvement in the time needed to cover the fourth and fifth trials (from a total of 5 trials with a 2-minute rest interval between each bout) of a distance of 100 yards. Similarly, Costill et al. (12) observed a spectacular improvement (42%) for the time until exhaustion in the fifth cycling bout at 100% VO₂max. Also, in a force-velocity test on a cycle ergometer (repetitive maximal 6-second sprints against increasing braking forces with a 5-minute between-sprint recovery period), it has been shown that NaHCO₃ ingestion improved performance by increasing the mean braking force (changed by the authors) during the bouts (7.0 kg in placebo condition vs. 7.9 kg in buffer condition, p < 0.001). Aschenbach et al. (1) reported data which contradicted those obtained in previous studies based on interval work, because they did not demonstrate enhanced performance in either peak power or total work performed during eight 15-second upper body sprints at maximum intensity with a 20-second rest. However, it has been suggested that the lack of improvement could be due mainly to (a) the short active re-
Table 1. Summary of the significant performance gains obtained in 16 studies after the ingestion of an alkalotic agent.*

<table>
<thead>
<tr>
<th>Study</th>
<th>Subjects</th>
<th>NaHCO₃ (g/kg)</th>
<th>Sodium citrate (g/kg)</th>
<th>Time elapsed (min)</th>
<th>Performance and intensity</th>
<th>Work time or distance</th>
<th>Total distance or work</th>
<th>Peak power (W)</th>
<th>Performance time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bird and Robbins (4)</td>
<td>12 middle-distance athletes</td>
<td>0.3</td>
<td>—</td>
<td>90</td>
<td>Track running “all out”</td>
<td>1,500 m</td>
<td>—</td>
<td>—</td>
<td>256.8 ± 36 253.9 ± 39</td>
</tr>
<tr>
<td>Costill et al. (12)</td>
<td>11 (10 men and 1 woman) healthy subjects</td>
<td>0.2</td>
<td>—</td>
<td>60</td>
<td>Cycling at 100% (Vo₂ₘₐₓ)</td>
<td>5 × 60 s cycling bouts, the fifth until exhaustion. 60 s rest interval between bouts</td>
<td>—</td>
<td>—</td>
<td>113.5 ± 12.4³ 160.8 ± 19.1³</td>
</tr>
<tr>
<td>Gao et al. (26)</td>
<td>10 male college swimmers</td>
<td>0.3</td>
<td>—</td>
<td>60</td>
<td>Swimming “all out”</td>
<td>5 × 100 yd (91.4 m) with 2 min rest interval between bouts</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Goldfinch et al. (29)</td>
<td>6 400-m male athletes</td>
<td>0.4</td>
<td>—</td>
<td>60</td>
<td>400 m</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>58.63 ± 2.25 56.94 ± 2.25</td>
</tr>
<tr>
<td>Lavender and Bird (56)</td>
<td>23 (15 women and 8 men) moderately trained subjects</td>
<td>0.3</td>
<td>—</td>
<td>60</td>
<td>Cycling “all out”</td>
<td>10 × 10 s sprints with 50 s rest interval between bouts</td>
<td>730.5 ± 123.6</td>
<td></td>
<td>745.4 ± 143.1</td>
</tr>
<tr>
<td>Linossier et al. (59)</td>
<td>8 (3 women and 5 men) moderately trained students</td>
<td>—</td>
<td>0.5</td>
<td>90</td>
<td>Cycling “all out” at 120% (Vo₂ₘₐₓ)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>258 ± 29 297 ± 45</td>
</tr>
<tr>
<td>McKenzie et al. (67)</td>
<td>6 healthy men</td>
<td>0.15</td>
<td>—</td>
<td>60</td>
<td>Cycling “all out”</td>
<td>6 × 60 s sprints with 60 s rest interval between bouts</td>
<td>121.6 ± 55.7 kJ 133.1 ± 53.2 kJ</td>
<td>—</td>
<td>74.7 ± 2.50 111.0 ± 3.05</td>
</tr>
<tr>
<td>McNaughton and Cedaro (73)</td>
<td>5 moderately trained men</td>
<td>0.3</td>
<td>—</td>
<td>95</td>
<td>Rowing ergometer “all out”</td>
<td>360 s 1,813 ± 6 m 1,861 ± 5 m</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>McNaughton and Cedaro (70)</td>
<td>10 moderately trained men</td>
<td>—</td>
<td>0.5</td>
<td>95</td>
<td>Cycling “all out”</td>
<td>120 s 67.9 ± 6.1 kJ 67.3 ± 7.9 kJ 1,132 ± 123 1,284 ± 113</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

*Table 1. Summary of the significant performance gains obtained in 16 studies after the ingestion of an alkalotic agent.*

---

**Legend:**
- P: Performance time
- B: Performance
- Vo₂ₘₐₓ: Oxygen uptake max

---

**Notes:**
- Data may contain rounding errors.
- Performance gains are significant at the 0.05 level unless otherwise specified.
- All studies indicate improved performance with the ingestion of alkalotic agents.
Table 1. Continued.

<table>
<thead>
<tr>
<th>Study</th>
<th>Subjects</th>
<th>NaHCO₃ (g/kg)</th>
<th>Sodium citrate (g/kg)</th>
<th>Time elapsed (min)</th>
<th>Performance and intensity</th>
<th>Work time or distance</th>
<th>Total distance or work</th>
<th>Peak power (W)</th>
<th>Performance time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>McNaughton and Thompson (69)</td>
<td>8 healthy men</td>
<td>0.5</td>
<td>—</td>
<td>1 d after chronic ingestion over a period of 6 d</td>
<td>Cycling “all out”</td>
<td>90 s</td>
<td>37.16 ± 0.50 kJ</td>
<td>39.36 ± 0.44 kJ</td>
<td>—</td>
</tr>
<tr>
<td>McNaughton et al. (75)</td>
<td>10 moderately trained women</td>
<td>0.3</td>
<td>—</td>
<td>90</td>
<td>Cycling “all out”</td>
<td>60 s</td>
<td>24.5 ± 0.7 kJ</td>
<td>26.9 ± 0.6 kJ</td>
<td>727.2 ± 33 769.4 ± 28</td>
</tr>
<tr>
<td>McNaughton et al. (77)</td>
<td>7 healthy subjects</td>
<td>0.5</td>
<td>—</td>
<td>1 d after chronic ingestion over a period of 5 d</td>
<td>Cycling “all out”</td>
<td>60 s</td>
<td>21.17 ± 0.97 kJ</td>
<td>24.12 ± 0.89 kJ</td>
<td>706.0 ± 23.1 779 ± 23.4</td>
</tr>
<tr>
<td>McNaughton et al. (78)</td>
<td>10 trained male cyclists</td>
<td>0.3</td>
<td>—</td>
<td>90</td>
<td>Cycling “all out”</td>
<td>60 min</td>
<td>839.0 ± 88.6 kJ</td>
<td>950.9 ± 81.1 kJ</td>
<td>—</td>
</tr>
<tr>
<td>Potteiger et al. (84)</td>
<td>8 trained male competitive cyclists</td>
<td>—</td>
<td>0.5</td>
<td>90</td>
<td>Cycling “all out”</td>
<td>30,000 m</td>
<td>—</td>
<td>—</td>
<td>3,562.3 ± 108.5 3,459.6 ± 97.4</td>
</tr>
<tr>
<td>Shave et al. (94)</td>
<td>9 (7 men and 2 women) elite triathletes and pentathletes</td>
<td>—</td>
<td>0.5</td>
<td>60</td>
<td>Track running “all out”</td>
<td>3,000 m</td>
<td>—</td>
<td>—</td>
<td>621.6 ± 31.4 610.9 ± 36.6</td>
</tr>
<tr>
<td>Wilkes et al. (106)</td>
<td>6 trained middle-distance athletes</td>
<td>0.3</td>
<td>—</td>
<td>60–180</td>
<td>Track running “all out”</td>
<td>800 m</td>
<td>—</td>
<td>—</td>
<td>125.1 ± 2.0 122.9 ± 1.9</td>
</tr>
</tbody>
</table>

* = all the references presented in this table have been published in impact factor journals.
† = placebo; B = buffer loading.
‡ = time to exhaustion in the fifth bout.
§ = in the fourth and fifth bouts.
¶ = during the final 10-second sprint (W).
¶ = sex not reported.
HCO₃ ingestion resulted in a small muscle alkalosis, but using a similar exercise duration, concluded that Na- 
maximum intensity. However, recently Stephens et al. (95), a cycle ergometer over a period of 60 minutes and at max-
imum intensity. During 5 series performed at 85% of 1 repetition maximum (1RM) on a leg press machine (83, 104). These researchers suggested that a slower rate of lactate and H⁺ production in resistance exercise, in contrast to other sporting activities such as high-intensity cycling, minimizes the possible benefits of increased extracellular pH and [HCO₃⁻]. Other researchers, however, have obtained positive results. Marist et al. (63) observed an improvement when a series of 10 leg press repetitions at 67.5% of 1RM were performed. Similarly, Coombes and McNaughton (11) found that the use of NaHCO₃ enhances the quantity of total work and peak torque reached when performing isokinetic flexions and extensions with the legs for 85 seconds at maximum voluntary intensity. Similarly, Verbitsky et al. (103) showed that NaHCO₃ was effective in increasing torque during isometric contractions evoked by percutaneous electrical stimulation in quadriceps femoris—a method employed to minimize problems associated with performance related to voluntary contractions—thus reducing muscle fatigue and enhancing recovery. This study is representative because it provides standardized testing protocols and ensures reproducibility of the testing conditions (see Figure 2).

**Main Results Obtained in High-Intensity Long-Term Exercise (More Than 2 Minutes).** Numerous studies have been undertaken to analyze the effects of NaHCO₃ administration in high-intensity, but longer-term activities (25, 27, 46, 47, 52, 73, 75, 79, 85, 86, 91, 95, 98), and the results are not conclusive. In this type of exercise, it is commonly argued that the ergogenic benefit is most likely to be due to the maintenance of optimal pH levels throughout the performance that would allow the competitor to perform at higher intensities or to perform a greater amount of work. For example, Cho et al. (9) obtained a reduction of 3.8 seconds in the time needed to cover a distance of 3 km with competition cyclists. Mc-
Naughton and Cedaro (73) observed an increase in the distance covered during a series of 6-minute bouts of exchange in a cycle ergometer test. Bird and Robbins (4) reported a significant improvement in the time needed to cover 1,500 m. We consider the study carried out by Mc-
Naughton et al. (77) to be representative of this type of exchange; they obtained an increase of 14% in the total work developed by trained cyclists (200–300 km·wk⁻¹) on a cycle ergometer over a period of 60 minutes and at maximum intensity. However, recently Stephens et al. (95), using a similar exercise duration, concluded that NaHCO₃ ingestion resulted in a small muscle alkalosis, but had no effect on muscle metabolism or intense endurance exercise performance in 7 endurance-trained men. These discrepancies were explained by the authors on the basis of different performance ride employed (i.e., 60-minute time trial [75] vs. "all out" for ~30 minutes at 75–80% VO₂max [95]). The differences found also could be due to subjects’ characteristics: 10 well-trained cyclists (VO₂max: 67.3 ± 3.3 ml·kg⁻¹·min⁻¹) with competitive time trial and physiological laboratory testing experience (75) vs. 6 well-trained triathletes and 1 cross-
country skier (VO₂max: 63.4 ± 2.0 ml·kg⁻¹·min⁻¹) after just one familiarization session with the experimental exercise protocol (95).

Although NaHCO₃ has been shown to have no effect on running time to exhaustion in constant load exercise (27, 46, 54), there may have been methodological problems associated with these studies. For example, in some studies subjects were not allowed to alter their running pace (exercise intensity) and could not, therefore, take advantage of the extra buffering capacity provided.

A special case within high-intensity, long-term exercises is that of prolonged intermittent type exercise. Recently, Price et al. (86) have shown that NaHCO₃ ingestion enabled 14-second cycling sprint performance to be maintained during 30-minute prolonged intermittent exercise (10 × 90 seconds at 40% VO₂max + 60 seconds at 60% VO₂max + 8 seconds of active rest + 14 seconds of maximal sprint + 8 seconds of active rest). The improvements in performance occurred during the initial 15 minutes of exercise, which was consistent with the time period when blood pH was changing rapidly (see Figure 3). This study is the first one to present data pertaining to more prolonged intermittent type exercise representative of many team sports.
The work of McNaughton and Thompson (78), however, is representative of the improvement in the performance. They verified the ergogenic effects of chronic vs. acute effects of NaHCO₃ ingestion for 6 days at a rate of 0.5 g·Kg⁻¹ vs. 0.5 g·Kg⁻¹·b.m. 90 minutes prior to exercise. It can be observed that (a) both the chronic and acute ingestion groups were significantly different from the control value ($p < 0.001$ and $p < 0.05$, respectively) in the performance of 90 seconds of maximal cycling ergometry, whereas there were no significant differences between the two groups beforehand; and (b) chronic ingestion allows subjects to perform more work, during short-term, high-intensity exercise, for at least 2 days after chronic ingestion of NaHCO₃ ends. These results indicate that athletes might use NaHCO₃ to improve performance on the day of competition without the significant side effects normally associated with the ingestion of NaHCO₃ in the doses needed.

The time elapsed from the ingestion of NaHCO₃ to the beginning of exercise (time of absorption) varies considerably in the different studies analyzed (see Table 1). Absorption times in different studies vary from 30 minutes (104) to 95 minutes (72), 105 minutes (103), 120 minutes (54), and 180 minutes (43, 97). The aim of the work carried out by Potteiger et al. (85) was to obtain the optimum absorption time. The authors demonstrated that, for an intake of 0.3 g·Kg⁻¹·b.m. of NaHCO₃, 120 minutes were needed to reach the peak pH and an average of 100–120 minutes to reach maximum [HCO₃⁻].

**SODIUM CITRATE**

**Acting Mechanism**

Sodium citrate, as such, is not found in body fluids. Immediately after ingestion it rapidly dissociates into the ions Na⁺ and citrate⁻. The citrate anion is expelled from the plasma, which means that the sum of cations and anions is modified, thus causing the electrical equilibrium to become unbalanced (14). Electrical neutrality is reestablished by means of a decrease in [H⁺] and an increase in [HCO₃⁻], which gives rise to the alkalotic state observed when this treatment is applied (16, 17, 94). A higher pH, induced by the ingestion of Na-citrate, may facilitate a greater efflux of Lac⁻ through the monocarboxylate transporter out of the working muscle, thereby favoring enhanced contractile performance of the muscle during exercise when compared to the same dosage of NaHCO₃ (17, 61, 80, 84). However, there are no conclusive studies on obtaining HCO₃⁻ from Na-citrate. Some scientists consider that the proton consumption and HCO₃⁻ production mechanisms which accompany the intake of Na-citrate are a consequence of liver oxidation (32).

Although sarcolemma is particularly impermeable to HCO₃⁻ (12, 47, 60, 61), a citrate is able to penetrate this membrane by means of a mechanism yet to be determined (14). Bicarbonate also needs a specific tricarboxylate carrier in order to penetrate the mitochondrial membrane (14). Within muscle fibers, citrate is an important cofactor in several metabolic processes (14): (a) it acts as a metabolic intermediary for the Krebs cycle (53, 96); (b) it transports units of acetyl CoA from the mitochondria toward the cytosol for the synthesis of free fatty acids during the postigestion phase preceding the exercise (14, 59); (c) it is a negative allosteric effector of the phosphofructokinase (PFK) (14, 48); and (d) by means of its effect on the mem-

---

**Figure 3.** Peak power output relative to the first sprint during NaHCO₃ and placebo trials (* denotes significant main effect between trials, $p < 0.05$). When expressed relative to the first sprint (14 seconds), peak power output was significantly greater throughout exercise in the NaHCO₃ trial than in the placebo trial, which evidenced decreases in peak power output with each sprint. (Reprinted from Med. Sci. Sports Exerc. 35: 1303–1308. 2003. Copyright © 2003 Lippincott Williams & Wilkins. Used with permission.)

[Doses Used](#)

The doses used in studies carried out with NaHCO₃ are varied (see Table 1). Seeking to determine the optimum quantity of NaHCO₃ that must be provided before the effort, McNaughton (69) tested 7 active subjects during 60 seconds of high-intensity exercise after the intake of 5 different doses (from 0.1 to 0.5 g·Kg⁻¹ body mass [b.m.]) of the above substance. The peak power reached was not significantly different from that reached when a placebo was used, until the dose given reached 0.3 g·Kg⁻¹·b.m. This fact might explain, partly, the lack of positive results obtained in the first studies, in which the quantity of NaHCO₃ supplied ranged from 0.1–0.2 g·Kg⁻¹·b.m. (12, 41).

Most of the studies analyzed used NaHCO₃ dose of 0.3 and 0.4 g·Kg⁻¹·b.m. (Table 1). An NaHCO₃ intake of 0.3 g·Kg⁻¹·b.m. produced an increase of approximately 4–5 mMol·L⁻¹ of the [HCO₃⁻] and 0.03–0.06 pH units in venous plasma 2–3 hours after ingestion (66). Even though venous blood pH does not coincide with that of arterial blood, it provides a reasonable indication of the changes which take place at this level (40, 96).

Those studies in which high-intensity and short-term exercises (less than 2 minutes) were used, and in which the doses of NaHCO₃ given were lower than 0.3 g·Kg⁻¹·b.m., did not generally produce an enhancement of performance, which might be due to the use of an insufficient dose or to the short duration of the effort (41). Therefore, it has been suggested that exercises lasting less than 1 minute may not be of sufficient duration for the glycolytic metabolism to activate completely, in that the capacity of the intracellular buffer is exceeded and a positive gradient between the intra- and extracellular medium is established (41, 65, 80). The main reason for the lack in performance improvement may consequently be due more to the exercise duration than to the doses used.
brane's potential, it can cause a reduction in the contraction threshold (14, 48). The effect of Na-citrate on lactate kinetics may be affected by the fact that the latter blocks the PFK (19). This blocking by citrate ingestion could restrict the use of glycolytic mechanisms, but allows a greater formation of lactic acid in long-duration exercises (more than about 180 seconds), long enough for this limitation to disappear (38, 59, 61), due to the suppression of an inhibitor (22). Therefore, Na-citrate works in a similar way to NaHCO₃ on plasma alkalization, but the exact nature of the mechanisms involved in the delay of exhaustion could be different and remains to be elucidated (59).

Main Research Carried Out Involving Na-citrate

Though much has been published on the use of NaHCO₃ as an ergogenic aid, the use of Na-citrate is still at an early stage of experimentation. Both substances present a parallel physiological behavior and the protocols used to assess the ergogenic effect of Na-citrate are designed to be similar to those discussed for NaHCO₃.

Main Results Obtained in High-Intensity Short-Term Exercise (Less Than 120 Seconds). A few studies have evaluated the ergogenic effects of Na-citrate in exercise durations less than 120 seconds (42, 50, 68, 81). McNaughton (68) recorded an ergogenic effect of both work and power output significantly improved on a cycle ergometer with exercise durations of 120 and 240 seconds. However, these benefits were not observed for exercise durations of 10–30 seconds. These results coincide with those showed by the rest of the studies we have analyzed (42, 50, 81). Kindermann et al. (50) could find no improvement in 400-m running time. Similarly, Ibañez et al. (42) showed that the Na-citrate administration did not improve performance during the simulated competitive 300-m run in 6 elite male 400-m runners. However, these authors suggested that an alternative explanation of the lack of ergogenic effects could be related to 2 methodological problems: (a) the small number of subjects that was used (which happens in the majority of the studies performed with elite athletes) and (b) the speed of the wind, which was sometimes more than negligible during the test (range, 3.1 m·s⁻¹ to −2.5 m·s⁻¹).

Main Results Obtained in Repeated Bouts Protocols. We have found just one study in which the effects of Na-citrate administration have been tested on a repeated bout protocol (102). In this work, the authors found no significant improvement in a protocol designed to simulate high-intensity intermittent exercise (five 45-s bouts) on a cycle ergometer. One explanation for this lack of improvement could be due to the lower dosage used that might not be enough to be effective (0.5 g·Kg⁻¹·b.m., see doses for citrate in Table 1).

Main Results Obtained After High-Intensity Long-Term Exercise (More Than 2 Minutes). There have been limited investigations into the use of Na-citrate as an ergogenic aid during high-intensity, long-term exercises and the results are in conflict (8, 22, 59, 64, 84, 93, 94). With respect to longer-term effort, the studies carried out by Shave et al. (94) and by Potteiger et al. (84) are significant (see Table 1). Shave et al. (94) found an improved 3,000-m running performance in elite multidisciplinary athletes. In this study, the improvement in performance came during the later stages of the race (laps 5 and 6). The authors postulated that it was during the later stages of the time trial that the potential negative effects of the H⁺ dissociated from Lac⁻ would be exhibited. Therefore, the ergogenic effect of Na-citrate could also occur at a comparable point. In a longer duration exercise, Potteiger et al. (84) recorded an improvement of 4% in the time needed to cover a total distance of 30 km by 8 competitive male cyclists. Also, Linossier et al. (59) verified an impressive enhancement, up to 40% of the total working time on a cycle ergometer at supramaximum intensity (120% of the Vo₂max). This intensity level favors the ergogenic effect of Na-citrate, since it directly involves the energetic systems which are hypothetically benefited (64). On the contrary, Schabort et al. (93) did not find any significant enhancement in the total time or in the power developed by 8 trained cyclists when covering a distance of 40 km. However, in this study, gastrointestinal discomfort and stomach cramps were experienced by 5 of the 8 subjects during the test, after ingestion of the 0.6 g·Kg⁻¹·b.m. citrate dose. So, the authors suggested that the failure of this citrate dose to produce improvements in performance was due to discomfort experienced by the cyclists. Also, in two investigations carried out in our laboratories (21, 23) we observed no improvement in maximum aerobic power during 2 incremental protocols with steps lasting from 1–4 minutes, or in the working loads at which the ventilatory threshold was reached. In a third study (22), we found no significant changes in the capacity to maintain high-intensity effort on a cycle ergometer, although there were differences of up to 9 seconds between the group given Na-citrate (0.4 g·Kg⁻¹·b.m.) and the one given the placebo.

Doses Used

Na-citrate is present in numerous foodstuffs, and there are even those who consider it to be a natural alkalization process for the human being (31). In fact, fruit juices and alkalotic salts have frequently been consumed with the object of increasing pH (31, 53). However, maintaining an alkalotic diet for several days does not seem to affect the blood’s acid-base balance, or to improve performance in supramaximum short-term effort (55).

In those studies that showed improved performances (Table 1), the doses used were 0.5 g·Kg⁻¹·b.m. and the time interval from intake to the beginning of exercise was approximately 120 minutes. Supporting this idea, Potteiger et al. (84) observed that, after supplying 0.5 g·Kg⁻¹·b.m. of Na-citrate, between 100 and 120 minutes were needed to reach the maximum pH and [HCO₃⁻] peak. Therefore, both the doses and the absorption time are, generally, higher than those needed for NaHCO₃. With this in mind, McNaughton (68) investigated the use of Na-citrate in varying dosages (0.1–0.5 g·Kg⁻¹·b.m.) and found that the 0.5 g·Kg⁻¹·b.m. was most effective as an ergogenic aid.

Aspects Applicable to Both Substances

Effects on pH, [HCO₃⁻], and [Lac⁻]

Regardless of whether any improvement was obtained, in most of the studies in which NaHCO₃ or Na-citrate was supplied with appropriate dosages and exercise durations (from 1–7 minutes), the common denominator is a pH, [HCO₃⁻] and [Lac⁻] blood peak higher than that found when a placebo was supplied (Figure 1). The interpretation given by the majority of the studies was that the
ingestion of alkalinizing agents increases the extracellular reserve of HCO₃⁻, thus enhancing the efflux of H⁺ and Lac⁻ from working muscles, which in turn decelerate the fall in intramuscular pH to the critical level from which glycolysis is partially inhibited and, consequently, ATP rate of production is decreased (12, 38, 43, 46, 47, 57, 58, 61, 64, 66, 97, 105).

Effects on Cardio-Respiratory Parameters
The cardio-respiratory parameters tend to be similar in both the alkalotic condition and with the placebo (13, 33, 35, 37, 52, 105), at least at submaximum working intensity. Robertson et al. (87) did not observe changes in oxygen consumption (VO₂), cardiac rate (CR), or tidal volume, in a group of subjects who performed different types of exercises of various intensities (23, 40, 61, or 80% of the VO₂max) after the ingestion of NaHCO₃ or placebo. Nevertheless, ventilation (VE) and respiratory frequency (FR) were less at 80% of the VO₂max in the group that was given the alkalotic drink. Similarly, studies performed in our laboratory (8, 20, 21, 22, 23) report an attenuated VE and a high CR in the group that ingested Na-citrate in relation to the control, when performing a maximal incremental test. Other studies (52, 59, 84) also record attenuated ventilatory dynamics after the intake of the alkaliizer. It is possible that a central control prevails over the peripheral regulatory mechanisms controlling VE, keeping it at a reduced level when faced with the increase in the state of the blood pH due to the alkalinization with Na-citrate.

Yet Chio et al. (10) obtained an enhancement of 5.5% of the VO₂max in the group that ingested NaHCO₃ in relation to the control group. Wijnen et al. (105), however, did not observe positive results in similar study conditions. Heck et al. (35) confirmed that NaHCO₃ ingestion did not attenuate the VO₂ slow component (i.e., change in VO₂ from minutes 3 and 4 to minutes 28 and 29 during constant-load exercise (30 minutes of cycling)) at an intensity above the lactate threshold. Similarly, in a recent study (91), it has been shown that NaHCO₃ ingestion did not significantly attenuate the VO₂ slow component (defined as the difference between end-exercise VO₂ and the VO₂ at the end of the third minute) of professional road cyclists during 2 bouts of 6 minutes duration at an intensity of 90% VO₂max interspersed with 8 minutes of active recovery.

Effects on Perceived Exertion
The effects of alkalic agents on perceived exertion (RPE) have been studied by several researchers (23, 25, 51, 87, 98, 99). Acid-base balance (pH, [HCO₃⁻], and [Lac⁻]) has been shown to influence the intensity of RPE during high-intensity arm and leg, as well as intermittent, exercise (87, 98). It has been argued that the mechanism underlying the relationship between acid-base balance and local RPE during exercise may involve negative effects of accumulation of intracellular H⁺ on force-generating capabilities of muscle as the muscle fatigues (87). During high-intensity exercise, the acidotic shift in muscle pH results in localized discomfort, and these sensory afferent signals affect the value a subject chooses on the RPE scale.

Kostka and Cafarelli (51) observed that RPE increased as blood pH decreased during induced acidosis in cycling exercise (15 minutes at 50% of VO₂max and 15 minutes at 80% VO₂max). Later on, Robertson et al. (87), when performing 3 modes of exercise (arms, legs and arms, and legs), found no buffer effect during intensities from 20–60% VO₂max, although at 80% VO₂max, RPE was lower after NaHCO₃ ingestion (0.3 g·kg⁻¹ b.m.). Swank and Robertson (98) during intermittent high-intensity exercise in a cycle ergometer, found that differentiated RPE for the legs, chest, and overall body were attenuated under alkalotic treatment (0.3 g·kg⁻¹ b.m.) relative to placebo. RPE was negatively correlated to the [HCO₃⁻] of venous blood, suggesting that RPE during this type of exercise could be related to buffering capacity of the blood. Recently, Swank and Robertson (99) studied the effect of NaHCO₃ ingestion (0.3 g·kg⁻¹ b.m.) on RPE during exercise recovery (3 × 5 minutes at 90% VO₂max, each separated by 10 minutes of recovery), indicating that the percentage of recovery of perceptual responses, in the early part of recovery, was increased in the buffer condition in comparison with placebo and control. In studies that have not found significant effects of alkalic agents on RPE, this could be due to the lower exercise intensities performed (25)—it may be that alkalosis reduces RPE at higher exercise intensities (87). It could be due also to the alkalotic substance and doses used; in our laboratory we used Na-citrate in doses of 0.4 g·kg⁻¹ b.m. (23), and we did not find any effect on RPE.

Comparison of Both Substances in Similar Protocols
Some studies have compared the effectiveness of Na-citrate to that of NaHCO₃ (1, 10, 67, 80, 81, 85, 100). Parry-Billings and McLaren (81) compared the 2 substances to determine which was more effective at enhancing anaerobic performance. For this purpose, they employed 3 types of compounds (at a dosage of 0.3 g·Kg⁻¹ b.m.) to different groups: NaHCO₃, NaHCO₃ + Na-citrate, and Na-citrate, 150 minutes before performing a 30-second Wingate Test. Even though the highest pH values, previous to exercise, were registered in the group given exclusively NaHCO₃, there were no significant differences in the total performance of the 2 groups. Total performance was slightly better in the group that ingested Na-citrate, followed by the group that was given NaHCO₃ + Na-citrate. No significant differences were found in the [Lac⁻] obtained in each condition. Tiryaki and Atterbom (100) recorded no significant changes in the time needed to cover a distance of 600 m after the intake of both substances (at a b.m. concentration of 0.3 g·Kg⁻¹) in relation to the control. Also, Potteiger et al. (85) studied the ingestion of Na-citrate (0.5 g·Kg⁻¹ b.m.) and NaHCO₃ (0.3 g·Kg⁻¹ b.m.), showing inconclusive results. In this work, a group of subjects performed an exercise in a stable state at the anaerobic threshold intensity for 30 minutes, followed by an effort until exhaustion at 110% of the anaerobic threshold for each of the conditions. No significant differences were obtained between the 2 situations in the time needed for the subjects to reach exhaustion, although metabolic conditions were considered to be more favorable during the submaximum phase for the group given Na-citrate. In summary, in order to compare the ergogenic power of both alkalic agents, studies examining the effects of ingestion of both agents during the same protocol are needed (77).

Negative Effects of the Ingestion of Alkalic Agents
With regard to negative effects, the Na-citrate solutions are preferred to those of NaHCO₃. This is because the
formers, with few exceptions (84, 93, 94), are not associated with the appearance of gastrointestinal upset, cramp, or diarrhea (2, 18, 80, 105). There seems to exist a direct relation between the appearance of these negative effects and the alkalotic dose used (57, 58, 68), although high doses of these substances are needed to induce an adequate modification of the acid-base state in the organism (63). These symptoms may be due to an increase in gastric emptying following the ingestion of alkalotic agents (80). When these compounds are consumed, there exists the possibility of an increased osmolality of the gastrointestinal tract and water may be shifted from the plasma to the intestine to counteract the hypertonicity (36, 58, 84). Moreover, the increase of [HCO₃⁻] in the blood requires a large quantity of water in the intestine to maintain the isotonic solution. In this respect, some researchers suggest that the intake of water ad libitum after supplying the alkalotic drink might alleviate the above-mentioned disorders (57, 58), although the degree of alkalois obtained might also be affected (36). Other studies have modified the administration path, using gelatin capsules, though these present the problem that a large number must be ingested (5, 54, 71, 85, 99). Intravenous administration has been used in a very few studies, with the aim of minimizing these gastrointestinal problems (30, 79, 105).

Ethical Considerations

The International Olympic Committee (IOC) does not explicitly ban the use of NaHCO₃ or Na-citrate (44). Nevertheless, since an excessively alkalotic urine may mask forbidden substances, such as anabolic agents, any athlete using this possible ergogenic aid may be held at the control point until his or her pH returns to normal (101).

Some researchers (18, 94, 107) believe the use of these agents may be considered a violation of the IOC Doping Rule, which states that athletes shall not use any physiological substance in an attempt to artificially enhance performance. In that sense, these authors have suggested that limits in the [HCO₃⁻] should be established in blood samples taken before competitions. However, other popular substances as creatine or caffeine are commonly accepted and used in many sport competitions.

Conclusions

The main problem associated with Na-citrate administration as an ergogenic aid is related to the lack of studies developed, though investigation with NaHCO₃ is starting to clarify its ergogenic value. Despite this, it is accepted that the disparity among the different results shown is basically attributed to the differences residing in the following: (a) the methodology used, which implies divergences in dosage and in the time elapsed between ingestion and the beginning of exercise (65); (b) the metabolic demands of the exercise task chosen (47, 84, 104); (c) the potential variability in an individual subject's responses to ingestion of NaHCO₃ (1, 52); (d) the fitness level presented by the subjects, so that in athletes with higher individual capacity to produce a greater amount of lactic acid during the exercise task chosen (i.e., trained subjects) the ergogenic effects of alkaline ingestion in a high-intensity exercise should be more significant than in subjects who have a limited maximal rate of anaerobic glycolysis (i.e., sedentary subjects) (42, 65, 69); and (e) the subjects' need to be completely familiarized with the testing protocols in order to produce consistent results, especially in endurance performance tests for cycling (92).

Independently of the type of protocol utilized (i.e., long-term vs. short-term duration), most of the studies support the idea that the ingestion of NaHCO₃ and Na-citrate seem to provide an ergogenic effect due to the establishment and maintenance of raised levels of pH during exercise (see Figure 1). A higher pH during the alkalinizing trial would facilitate Lac⁻ and H⁺ efflux from the working muscle, thereby producing enhanced contractile performance of the muscle during exercise. The results of the effects of buffer administration on performance found in the literature are conflicting, perhaps because the maximum buffering capacity of the muscle is not challenged equally by all exercise protocols. Although some studies used protocols in which a fixed distance had to be completed in the fastest time possible or the most work was performed in a given time, other tests were open-ended and the subjects were to perform until exhaustion. So, it could be that the buffer substance administration may improve performance during one type of exercise protocol but not on another. In this regard, there is sufficient data to suggest that when exercise protocols of short duration (30–40 seconds or less) are used, alkaline agents have minor or no effect on performance (42, 69, 73, 81). In these types of protocols, maximal pH changes do not occur repeatedly, and therefore the maximum buffering capacity is not used (81), limiting the potential benefits of any additional effect of an exogenous buffer. Nonetheless, if sufficient duration and intensity are reached in the exercise bouts and these efforts are repeated with the appropriate frequency (i.e., intermittent exercise), H⁺ production is increased so that the enhanced blood buffering capacity induced by the buffer exogenous administration may speed up the recovery between efforts so that the power output is maintained during subsequent efforts, as seen in Table 1 (93). So, there exists a generalized consensus that the ingestion of NaHCO₃ or Na-citrate prolongs high-intensity exercise (between 80 and 125% VO₂max) with a duration of 1–7 minutes (57, 69, 70, 71, 72, 74, 76, 78). With regard to longer efforts, there are not enough data to be conclusive. However, when aerobic athletes work at intensities at or above the lactate threshold during competition, the use of NaHCO₃ or Na-citrate loading may facilitate Lac⁻ and H⁺ efflux, and therefore, the delay of muscle fatigue. Further work into the role of pH on Lac⁻ and H⁺ efflux from working muscles is needed (64, 95).

Practical Applications

On the basis of the studies analyzed, we may conclude that benefits from the exogenous ingestion of NaHCO₃ and Na-citrate are obtained in activities with a duration sufficient to generate a difference in the H⁺ ion gradient, and thus generate a difference between trials (64). These activities are very high intensity, recruit fast motor units, and involve large muscular groups (see Table 1); sports such as soccer, cycling time trials (i.e., mountain-bike down-hills or track and road cycling), and some athletics trials (i.e., 800-, 1,500-, 3,000-, 10,000-m) may benefit from the use of these alkalotic substances. Benefits are also obtained by administration of a dose timed to allow the maximum tolerable alkalotic level to develop at the moment exercise starts (i.e., 0.3 g·Kg⁻¹ b.m. of NaHCO₃ and 0.5 g·Kg⁻¹ b.m. of Na-citrate), and to accommodate a
specified absorption time (i.e., 90 minutes for NaHCO₃ and 120 minutes for Na-citrinate). It has been confirmed, however, that the effect of these alkalotic agents is not exempt from great individual variability (20, 59, 83). Consider, for example, differences in the physical conditioning of the subjects (83, 93) or individual gastrointestinal tolerance. Paradoxically, with Na-citrate, a higher dose may have to be used to get an ergogenic effect (i.e., 0.6 g·Kg⁻¹·b·m.) and the predicted enhancement could be limited by the associated gastrointestinal problems (93, 98).

For correct use of both substances in competition, avoiding gastrointestinal distress, it is suggested that (a) the competitive use of NaHCO₃ or Na-citrurate should be preceded by individualized familiarization trials during training (94); (b) the ingestion of water ad libitum should be facilitated during treatment; (c) when NaHCO₃ is given (because no study examining the effect of chronic Na-citrurate ingestion has been analyzed) chronic ingestion for 5–6 days is suggested, with intake stopping 2 days before the competition (71, 76); and (d) an alternative to avoid all these oral ingestion related problems is the intravenous infusion of the alkalotic substance (31, 79, 105), although this procedure can be refused by the athletes.

REFERENCES


Acknowledgments
The authors gratefully acknowledge Dr. M. Price for useful comments on a previous version of the manuscript.

Address correspondence to Bernardo Requena, brequena@ugr.es.