PERSPECTIVES (PERSPECTIVAS)

MISCONCEPTIONS: BICARBONATE AS AN ERGOGENIC AID? A PHYSICAL, CHEMICAL, MECHANISTIC VIEWPOINT.

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ABSTRACT

KAY, B. Misconceptions: Bicarbonate as an ergogenic aid? A physical, chemical, mechanistic viewpoint. Brazilian Journal of Biomotricity, v. 2, n. 4, p. 205-219, 2008. The ergogenic effect of sodium bicarbonate has been extensively studied. Results have been equivocal. Bicarbonate (HCO_3^-) is widely proposed as having a possible ergogenic effect via an attenuation of exercise induced acidification, and / or via increased rapidity of lactate export from working muscles. Lactate is cited as being co-exported with protons, in a 1:1 stoichiometry. With respect to the model proposing bicarbonate as an ergogenic aid: (a) exercise induced acidosis may not be deleterious to exercise performance; (b) both [HCO_3^-] and [H^+] are dependant variables and therefore unable to be primarily or independently moderated; (c) The finding that ingestion / infusion of $NaHCO_3$ results in increased lactate export rate from working muscles is not universal (d) whether or not protons are co-exported from muscle cells with lactate is irrelevant to [H^+] in either case; and finally (e) lactate is not apparently causally involved in muscle fatigue development. Rather, exercise leads to accumulation of extracellular K^+ and intracellular Na^+ which may disturb the fluid balance of cells, and the continuing excitability of cells. In conclusion, the current author suggests that the likely ergogenic agent is the Na^+, rather than the HCO_3^-; which may operate by mitigating such osmotic and ionic perturbations. The ergogenic affect of Na^+ appears from an initial investigation, to be maximised when administered with bicarbonate; as opposed to with chloride, citrate, or lactate.

Key Words: Metabolic acidosis, Muscle pH, Lactate, Muscle Fatigue, ATOT, SID+, Stewart model.

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Notation
Brackets denote 'concentration of': e.g. the concentration of H^+ is denoted as $[H^+]$.

SID^+ is the net positive electrochemical charge due to the net concentrations of all strongly dissociated ions (mEq), of which the most computationally important are Na^+, K^+, Cl^-, and lactate$^-$.

A_{TOT} is the concentration of all 'weak acids, plus their anions modelled as a single variable (according to the net equilibrium constant, which depends on the concentration and speciation of A_{TOT}, the SID^+, the partial pressure of CO_2, and the temperature of the solution). In plasma, the most computationally important proteins are albumin and globulins.

INTRODUCTION

Bicarbonate (HCO3-) is a proposed ergogenic aid (BISHOP & CLAUDIUS, 2005; BISHOP et al., 2004a; BISHOP et al., 2004b; FORBES et al., 2005; KOLKHORST et al., 2004; MATSON & TRAN, 1993; MAUGHAN, 2003; NIELSEN, et al., 2002; PRICE et al., 2003; SANTALLA et al., 2003; SOSTARIC et al., 2006; STEPHENS et al., 2002; VAN MONTFOORT et al., 2004). The proposed mechanism is that the bicarbonate ion is claimed to attenuate exercise-induced acidosis via the Henderson relationship (BISHOP et al., 2004; NIELSEN et al., 2002; SOSTARIC et al., 2006; VAN MONTFOORT et al., 2004). One proposed means of deriving ergogenesis is therefore from ingestion or infusion of sodium bicarbonate (NaHCO3), which dissociates to provide the HCO3-. Exercise-induced acidosis has been linked with muscle fatigue in electrically stimulated, mechanically skinned, deceased frog muscle fibres at 12°C (FITTS, 1994; FITTS & BALOG, 1996). However; in healthy, living mammalian muscle fibres, such performance decrement under acidification is abolished (BRUTON et al., 1998; NIELSEN et al., 2001; PATE et al., 1995; PEDERSEN et al., 2003; PEDERSEN et al., 2005; PEDERSEN et al., 2004; WISEMAN et al., 1996), probably because of other compensatory homeostatic mechanisms concomitant with the acidity: e.g; up-regulation of the creatine kinase reaction, rightward shift of the oxy-hemoglobin / oxy-myoglobin dissociation curves, increased muscle cell excitability, etc (BRUTON et al., 1998; NIELSEN et al., 2001; PATE et al., 1995; PEDERSEN et al., 2003; PEDERSEN et al., 2005; PEDERSEN et al., 2004; WISEMAN et al., 1996). Notwithstanding such criticisms, the proposed mechanism of [H+] control via ingestion / infusion of sodium bicarbonate is described via the classic Henderson equation, which proposes that [H+] is a dependent variable, and that [HCO3-] is an independent variable affecting [H+] according to the constants S and Kc : described later herein. A second possible explanation for ergogenesis from bicarbonate is somewhat interconnected with the first, and involves the export of lactate from working muscle cells:

Lactate is thought by some to be causally involved with acute muscle fatigue development; therefore expedited export of lactate from working cells appears to be indicated. However, the assertion that lactate induces muscle fatigue in situ is also challenged extensively elsewhere (DRAKE et al., 1980; MENGUAL et al., 2003; NIELSEN et al., 2001; PHILP et al., 2005; SAMAJA et al., 1999; SUMIDA et al., 2006; VAN MONTFOORT et al., 2004). Nonetheless, lactate is exported from working muscle cells dependant primarily on its intracellular to extracellular concentration gradient (MENGUAL et al., 2003). The export of lactate is undertaken by monocarboxylate transporters (JUEL, 1997) which may (BISHOP & CLAUDIUS, 2005; BISHOP et al., 2004; BISHOP et al., 2004;

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FORBES et al., 2005; KOLKHORST et al., 2004; MATSON & TRAN, 1993; MAUGHAN, 2003; NIELSEN et al., 2002; PRICE et al., 2003; SANTALLA et al., 2003; SOSTARIC et al., 2006; STEPHENS et al., 2002; VAN MONTFOORT et al., 2004) or may not (CONSTABLE, 2000; LINDINGER et al., 2005; SIRKER et al., 2002; STAMPFLI et al., 2006; WOOTEN, 2003) involve an obligatory 1:1 co-transport of H+. Theoretically, if H+ were an independent variable (it is not, this will be discussed later), and H+ were co-transported; then alkalinisation of the extracellular fluid should facilitate more rapid lactate export. This is because lowered extracellular [H+] would alleviate any allosteric inhibition of lactate export imposed by a build up of extracellular [H+]. Indeed, when the plasma and interstitial fluid is alkalinized, some researchers have noted increased cellular lactate export rates under exercise stress (BISHOP & CLAUDIUS, 2005; FORBES et al., 2005; PRICE et al., 2003; SANTALLA et al., 2003), however others have not (BISHOP et al., 2004; NIELSEN et al., 2002; SOSTARIC et al., 2006; STEPHENS et al., 2002).

Whether H+ is or is not co-transported, the intra and extracellular [H+] are dependent largely upon the transport of lactate / pyruvate across the sarcolemmae in either direction; because of the effect this has on the electrochemical charges of the fluid pools concerned (CONSTABLE, 2000; LINDINGER et al., 2005; SIRKER et al., 2002; STAMPFLI et al., 2006; STEWART, 1981; WOOTEN, 2003). To elucidate; an alternative approach to modelling [H+] control provided by Stewart (STEWART, 1978; STEWART, 1981; STEWART, 1983) dictates rather, that both [HCO3-] and [H+] are dependant variables within a larger set of real-world constraints, both physical and chemical in nature; and therefore are both unable to set their own concentrations. By way of summary, all fluid pools must adhere to the laws of physics, specifically the Newtonian laws of conservation (of mass and energy), and also the chemical law of electroneutrality (after Stewart). Basically, water auto-ionises and auto-reforms from its constituent ions (H+ and OH-) to a degree dependent upon the energy in the system: ionisation requires an energy input (is a cooling influence), reformation releases free energy (is a heating influence). Both reactions simultaneously proceed in opposition to one another. Therefore the temperature of the system is one determinant of the equilibrium balance. This is an example of Le Chatellier's principle in action. Secondly, the presence of ions and the freedom of those ions' concentrations to change over time (the most computationally important being Na+, K+, Cl-, and lactate), would affect the net electrochemical charge of the fluid pool were this not counteracted. The result would be a massive electrical discharge through the fluid pool. This is therefore, counteracted by the dissociation constants of all the other H+ 'donors' automatically changing, and therefore the fluid changing in such a way as the net charge remains zero. Thirdly, the presence of proteins with fixed negative charges (mainly albumin and globulins in human plasma) means that a change in the concentrations of these proteins will affect the [H+], as fixed negative charges attract H+ according to the specific K value concerned. Finally, the partial pressure of CO2 exerts an effect on [H+] via the Henderson relationship. Once understood, readers will see that the dictates of the Stewart model indicate that it is the addition of Na+ which leads to the change in [H+], and not the bicarbonate. In practice, ingestion / infusion of

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sodium (with bicarbonate) has indeed been shown to reduce plasma and interstitial fluid pool [H+], however with varying predictability (BISHOP & CLAUDIUS, 2005; BISHOP et al., 2004a; BISHOP et al., 2004b; FORBES et al., 2005; KOLKHORST et al., 2004; MATSON & TRAN, 1993; MAUGHAN, 2003; NIELSEN et al., 2002; PRICE et al., 2003; SANTALLA et al., 2003; SOSTARIC et al., 2006; STEPHENS et al., 2002; VAN MONTFOORT et al., 2004).

Despite the polemic provided above, the possibility of a practical ergogenic effect from bicarbonate ingestion or infusion, has been extensively studied in the past and more recently also; e.g. (BISHOP & CLAUDIUS, 2005; BISHOP et al., 2004; BISHOP et al., 2004; FORBES et al., 2005; KOLKHORST et al., 2004; MATSON & TRAN, 1993; MAUGHAN, 2003; NIELSEN et al., 2002; PRICE et al., 2003; SANTALLA et al., 2003; SOSTARIC et al., 2006; STEPHENS et al., 2002; VAN MONTFOORT et al., 2004). Exercise performance outcomes following sodium bicarbonate ingestion / infusion have been equivocal at best, and this trend continues. Specifically, sodium bicarbonate had 'no significant effect' on intense endurance cycling (STEPHENS et al., 2002), 'no significant effect' on prolonged intermittent cycling (PRICE et al., 2003), and 'no significant effect' on intermittent sprint running (BISHOP & CLAUDIUS, 2005). On the other hand, others have claimed 'improved performance' in 2000m rowing time trials (NIELSEN et al., 2002), 'improved performance' in 6s repeated sprint cycling bouts (BISHOP et al. 2004), 'improved performance' in running time to exhaustion at fixed speed (VAN MONTFOORT et al., 2004), improved performance in 200m swimming (CERRETELLI & SAMAJA, 2003) and 'improved performance' in finger flexion time to exhaustion (SOSTARIC et al., 2006). There seems therefore, to be no discernable pattern of results when exercise modality or intensity are considered, thus the reasons for the equivocal results remain obscure. The purpose of this review therefore, is to elucidate on the arguments provided above, and to provide an alternative hypothesis regarding the utility of sodium bicarbonate as an ergogenic aid, and the likely mechanism of its action. The current author proposes that the sodium ion is the potential ergogenic aid (and not the bicarbonate), and its action is most likely through attenuation of ionic and fluid shifts concomitant with exercise, rather than any attenuation of acidification.

[H+] CHANGES IN SKELETAL MUSCLE FIBRES DURING EXERCISE

The [H+] in the blood plasma of healthy humans ranges from ~3.98E-08 Mol.L-1 at rest; to ~15.8E-08 Mol.L-1 at the point of volitional exhaustion following an incremental exercise test to exhaustion over 8-12 minutes duration. Typically, physiologists will refer to this as a pH shift from ~7.4 to ~6.8. This represents a change from ~4 parts per 100,000,000 to ~16 parts per 100,000,000. The intracellular pH of whole muscles is also similarly regulated: from ~7.0 at rest to between ~6.8-6.4 at exhaustion, depending on the specific muscle concerned, the exercise modality, and individual differences (BANGSBO et al., 1993; OELBERG et al., 1998; SAHLIN et al., 1978). Further, muscle fibre types differ

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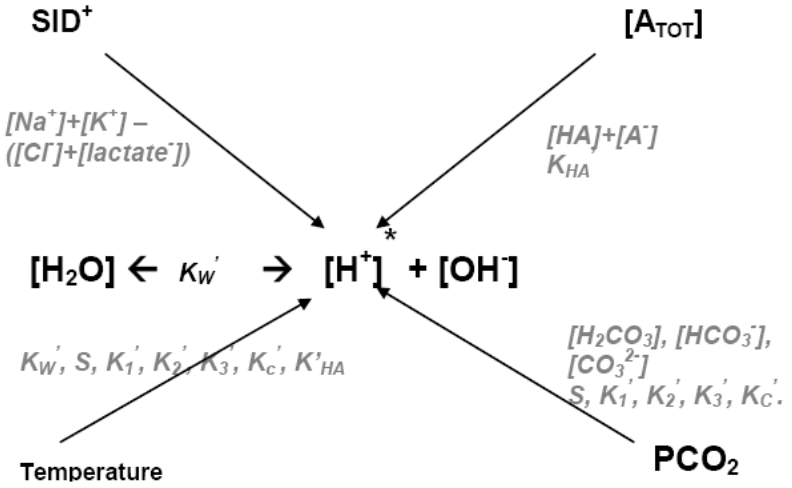
in this respect, with highly glycolytic fibres reaching a pH of ~6.2 while highly oxidative fibre pH tends to drop less; to ~6.9 (ACHTEN et al., 1990). If intramuscular pH drops from 7.0 to 6.2, this equates to a [H+] change from ~10 parts per 100,000,000 to ~63 parts per 100,000,000. The mechanisms behind control of [H+] are multifaceted, complex, interactive, and inherently homeostatic. In describing the mechanisms behind [H+] control in mammalian body fluids, scientists should consider three relevant physical and chemical laws, which act simultaneously; i.e. the approach of the late Peter Stewart (STEWART, 1978; STEWART, 1981; STEWART, 1983). Stewart describes the physical and chemical constraints which determine [H+] from the standpoint of: (a) Newtonian laws (conservation of mass and energy), (b) the law of conservation of electro-neutrality (After Stewart), and also (c) Le Chatellier's Principle with respect to the temperature dependence of pH.



*H^+ is a construct: this chemical species actually exists in the form of H_3O^+.

*SID^+ is the net electrochemical charge differential due to the net concentrations of strongly dissociated ions, of which the most computationally important are Na^+, K^+, Cl^-, and $lactate^-$.

*A_{TOT} is the concentration of all 'weak acids, plus their anions modelled as a single variable (according to the net equilibrium constant, which depends on the concentration and speciation of A_{TOT}).

Figure 1 - Relationships between the four independent variables PCO2, SID+, [ATOT], and temperature; and the dependant variable [H+]. [HCO3-] is also shown to elucidate its position in the control hierarchy as another dependant variable. pH can only be moderated by moderating one of the four independent variables.

The relevant 'take-home' messages from Stewart are:

1. The independent variables are SID+, [ATOT], PCO2 and temperature only.

2. Other factors which affect pH are the 'constants' KW', S, KC', K1', K2', K3', and KHA'. These are considered constants because they cannot be externally manipulated other than by changing temperature or ionic strength of the solution (i.e. temperature and/or SID+ and/or [ATOT], and/or PCO2).

3. [H+] is therefore a dependant variable. It cannot be primarily or independently

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moderated (CONSTABLE, 2000; LINDINGER et al., 2005; SIRKER et al., 2002). This model suggests that the aqueous solution has basically an inexhaustible capacity to buffer any H+ 'added' to the solution and also basically an inexhaustible capacity to 'produce' H+ when they are 'removed' from the solution. This occurs in order to maintain electro-neutrality via changes in KW', S, KC', K1', K2', K3', and KHA'. The most potent effecter of [H+] during exercise is the accumulation of lactate-, which lowers the value of SID+, hence draws H+ into solution via changes in KW', S, KC', K1', K2', K3', and KHA'. This occurs in order that the net electrochemical charge of the fluid pool concerned remains zero.

4. [HCO3-] is also a dependant variable, and therefore also cannot be primarily or independently moderated (CONSTABLE, 2000; LINDINGER et al., 2005; SIRKER et al., 2002). HCO3- has been used by many researchers as an independent affecter of pH: According to the dictates of the Stewart model, this is impossible. Any change in [H+] attributable to sodium bicarbonate ingestion or infusion is due entirely to the affect of the Na+ on the SID+. 'Added' bicarbonate simply exits the plasma as CO2 gas, and the remainder is H2O. This evolution of HCO3- occurs according to the value of the 'constants' S and KC. The addition of the sodium changes the value of SID+, and hence some of the added bicarbonate remains, however the 'take home' message is that [HCO3-] cannot primarily affect [H+], and [HCO3-] cannot be independently set by the researcher.

ACIDOSIS AS A CAUSE OF ACUTE MUSCLE FATIGUE?

Does intracellular acidosis cause fatigue?

The following section provides four arguments for exercise-induced acidosis as a utilitarian, and indicated process overall: Firstly, exercise produces lactate, lactate causes acidity because it reduces the value of SID+. Increased intracellular [H+] deleteriously affects the enzyme 'phosphofructokinase' (E.C.2.7.1.11), the 'rate-limiting' enzyme in glycolysis (SPRIET, 1991). Acidosis also may directly interfere with the contractile proteins' functioning (FITTS, 1994; FITTS & BALOG, 1996). However, Spriet (1991) shows why these assertions are an example of reductionism, as increased [H+] also has the effect of up-regulating the enzyme 'AMP deaminase' (E.C.3.5.4.6) (KATO et al., 2004; KATO et al., 2005). This in turn has two counterbalancing effects on the phosphofructokinase reaction rate: (a) due to the low K value of NH3, the production of NH3 by E.C.3.5.4.6, actually results in an accumulation of NH4+. This increases the value of SID+, hence tends to lower [H+] (CONSTABLE, 2000; LINDINGER et al., 2005; SIRKER et al., 2002); and (b) NH4+ directly up-regulates E.C.2.7.1.11 (KATO et al., 2004; KATO et al., 2005). Indeed, it has been shown in situ, that phosphofructokinase activity is well matched to the ATP demand despite decreases in muscle pH to ~6.4 (SPRIET, 1991).

Secondly, the activity of the creatine kinase (E.C. 2.7.3.2) reaction is up-regulated by increasing [H+], and it too acts to reduce [H+] again, because PCr carries a '2-' electrochemical charge (LINDINGER, 1995). When it is used to form ATP + Cr (see below) this 2- charge is abolished (LINDINGER, 1995).

ISSN 1981-6324

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$PCr^{2-} + ADP + H^{+} \leftarrow E.C.\ 2.7.3.2 \rightarrow ATP + Cr.$

(NB: the H+ is shown for stoichiometric correctness only).

Thirdly, intracellular [H+] has been suggested as a performance limiter because of a proposed effect on the cellular red-ox potential, i.e. the NAD+ : NADH ratio:

$Lactate + NAD^{+} \leftrightarrow Pyruvate + NADH + H^{+}$ (Barron, Gu & Parrillo 2000; Mengual et al. 2003).

(NB: the H+ is shown for stoichiometric correctness only).

Increased [NADH] with respect to [NAD+] has been proposed to exert allosteric inhibition of the pyruvate dehydrogenase complex (E.C:1.2.1.51, E.C:1.2.4.1, E.C:2.3.1.12, & E.C:1.8.1.4). Increasing [H+] will tend to drive this equilibrium left; favoring the formation of lactate and NAD+ the oxidized form of the co-factor, thus the formation of lactate ameliorates. However, this has no effect on [H+], as the H+ is shown for stoichiometric correctness only, according to the dictates of the Stewart approach. Both lactate and pyruvate can be imported / exported, so that homeostasis is maintained (BARRON et al., 2000; MENGUAL et al., 2003). Also, pyruvate can enter / exit the cell fluid via anaplerosis / cataplerosis (Macdonald et al., 2005).

A fourth reason to consider exercise induced acidity as an indicated and utilitarian process can be derived from research indicating that inorganic phosphate (which may pool during intense exercise due to ATP hydrolysis) can passively enter the sarcoplasmic reticulum (SR) and precipitate out of the cytosol along with calcium ions (ALLEN et al., 2002; ALLEN et al., 2008; ALLEN & WESTERBLAD 2001; DAHLSTEDT et al., 2001; DAHLSTEDT & WESTERBLAD, 2001; WESTERBLAD et al., 2002). This obviously compromises the muscle cell function due to the reliance of muscle function on SR Ca2+, however increased [H+] strongly discourages this form of precipitation (LU & LENG, 2005). In summary, it appears that intracellular [H+] remains within a normal, and indicated physiological range during rest and exercise in health. Increased intracellular [H+] within this range does not appear to adversely affect physical function at the whole body level.

Intracellular [H+] is lowered by lactate export leading to extracellular acidosis.

Lactate is exported from working muscle cells depending primarily on the intracellular to extracellular [lactate] gradient (JUEL, 1997; MENGUAL et al., 2003). The main exporters of lactate are glycolytic fibres. This apparently makes sense as these fibres have derived the energy they can from glycogenolysis, but are poor in mitochondria. Thus, much of the lactate exported from glycolytic fibres is taken up by oxidative fibres and completely oxidised there (PHILP et al., 2005). Much of the remainder is used by the liver

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for gluconeogenesis, which is important because glycogen is refilled intra-contractions from blood glucose (SHULMAN, 2005; SHULMAN & ROTHMAN, 2001). It is suggested in the literature that intracellular and extra-cellular [H+] are co-controlled through the co-transport of H+ along with lactate and pyruvate by the monocarboxylate transporters; mainly MCT1 and MCT4 in human muscle cells (JUEL, 1997; MENGUAL et al., 2003). In support of the assertion, Juel (1997) showed that pH changes across the sarcolemma were well correlated with the movement of lactate, and identified a proton binding site on the MCTs. Protons, being particularly reactive will bind readily to fixed negative charges such as those found on MCTs. This often causes the protein concerned to undergo conformational changes and thus 'activate' the transporter. However, Stewart's approach dictates that the change in [H+] on either side of the sarcolemma is due entirely to the addition or subtraction of lactate to or from the fluid pool concerned, and not proton co-transport. If the Stewart model is applied to this problem, it will reveal that whether a proton is or is not actually transported with the lactate / pyruvate, it is quite irrelevant. This is so, as [H+] is a dependent variable according to the model, and only changes in the value of the four independent variables given above will change the [H+]: i.e. the fluid pools will re-equilibrate within 10-6.s according only to the values of those four variables, according to their effects on the constants KW', S, KC', K1', K2', K3', and KHA'.

Does extra-cellular acidosis cause fatigue?

Notwithstanding the above, some previous authors have noted increased lactate export rates associated with decreased extra-cellular [H+] (BISHOP & CLAUDIUS, 2005; FORBES et al., 2005; PRICE et al., 2003; SANTALLA et al., 2003), however this finding is not universal (BISHOP et al., 2004; NIELSEN et al., 2002; SOSTARIC et al., 2006; STEPHENS et al., 2002). The proposed limitation being allosteric as the co-transport model suggests. Given that the Stewart interpretation demands that no such allosteric limitation is actually in effect, other mechanisms behind this phenomenon should therefore be considered by future researchers. In practice, it has been suggested (SPRIET, 1991) that intracellular [H+] will drop predictably when extracellular [H+] is lowered: but the change in intracellular pH is dampened with respect to the change in extracellular pH. The values given indicate that a +0.10 pH change outside the cell at rest results in a +0.07 pH change inside the cell at rest (SPRIET, 1991). The movement of lactate out of muscle cells cannot be considered ergogenic because it ameliorates some proposed interference with contractile function as discussed. However, increased rapidity of lactate export might be ergogenic because it provides a vast supply of substrate for oxidative metabolism. Either way, it seems extracellular acidity is unlikely to be the cause of any delay in lactate export. There seems to be little evidence that extracellular acidity is problematic within the physiological range in situ.

The classic study upon which the assertion that extra-cellular acidosis is problematic to exercise performance involved a frog muscle fibre which was skinned, attached to a force transducer, and bathed in a test tube at 10-12°C.

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The fibre was electrically stimulated to contract, force measurements taken, and then the test tube was acidified. This resulted in force decline (FITTS, 1994; FITTS & BALOG, 1996). However, this phenomenon does not occur in in-tact mammal fibres at the correct physiological temperature (BRUTON et al., 1998a; BRUTON et al., 1998b; NIELSEN et al., 2001; PATE et al., 1995; PEDERSEN et al., 2003; PEDERSEN et al., 2005; PEDERSEN et al., 2004; WISEMAN et al., 1996). Rather, it appears extra-cellular acidosis may play a protective role in muscle function via counteracting the effects of extra-cellular K+ accumulation via increased Cl- conductance, perhaps (BRUTON et al., 1998; PATE et al., 1995; SOSTARIC et al., 2006). Further, other evidence that extra-cellular acidosis is utilitarian and indicated can be found in the positive effect it has on the oxy-haemoglobin dissociation curve (STRINGER et al., 1994). In summary, it does not appear that exercise-induced acidosis of the extracellular fluid plays a causal role in fatigue development.

It remains possible however, that reduced plasma pH may exert some effect on peripheral neural and central fatigue mechanisms which are yet to be elucidated.

Why is bicarbonate not likely to be ergogenic?

'Sodium bicarbonate (NaHCO3) dissociates strongly in water to form Na+ + HCO3-. The bicarbonate thus added should end up exiting the system via:

$$H^+ + HCO_3^- \leftrightarrow H_2CO_3 \leftrightarrow H_2O + CO_2$$

and it would, according to Le Chatellier's principle, were it not for the change in [Na+] altering the value of SID+ such that [H+] tends to drop and therefore attenuates the 'rightward shift' indicated above. Therefore, the independent variable that has been manipulated is SID+, and not [HCO3-], which moves its equilibrium concentration according to the effect of changed SID+ on the constants KW', S, KC', K1', K2', K3', and KHA'. Given that salt also contains Na+, readers may at this point be wondering 'why then, does salt not apparently produce an alkalinising effect in the manner sodium bicarbonate does'. The ingestion or infusion of salt (NaCl) results in a strong dissociation to Na+ + Cl-. The Na+ which enters the system via dissociation of salt leads to an immediate (10-6.s) 'rightward shift' in another equilibrium; the sodium bicarbonate equilibrium described by:

$$K = [HCO_3^-][Na^+]/[NaHCO_3].$$

This leaves an 'unmatched' Cl- electrochemical charge differential, which means SID+ is lowered, and [H+] must increase via a change in KW', S, KC', K1', K2', K3', and KHA' so as to maintain electro-neutrality (Constable 2000; Lindinger et al. 2005; Sirker et al. 2002). This phenomenon is known as hyperchloremic acidosis (CONSTABLE, 2003). For this reason alone, bicarbonate studies using NaCl as a 'placebo' e.g. (BISHOP & CLAUDIUS, 2005; BISHOP et al., 2004; NIELSEN et al., 2002; PRICE et al., 2003) are thus

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questionable with respect to validity according to the physiochemical model'. Notably however, one previous research group (VAN MONTFOORT et al., 2004) have compared all permutations of four different sodium salts and assessed differences between conditions with respect to a performance outcome (time to exhaustion), which may well be a preferable procedure on the basis of the above.

Summary: Sodium (with bicarbonate) as an ergogenic aid?

In summary, the bicarbonate ion is offered as a potential ergogenic aid by many researchers because it is believed to ameliorate exercise induced acidosis. Notwithstanding the evidence suggesting the acidosis concomitant with exercise in healthy individuals is not likely to limit exercise performance, when sodium bicarbonate is ingested, with stomach pH as low as it is, virtually all of the HCO3- is evolved as CO2 and water. Only with subsequent alkalinization of gastric contents, and with flow of gastric contents into the upper intestine, is a blood-like acid-base profile attained. Many researchers have therefore chosen to infuse sodium bicarbonate directly to the blood. Researchers tend to assert that extracellular alkalinisation may be ergogenic as it may expedite lactate efflux from muscle cells. However: (a) although extracellular alkalosis may reduce the resistance to lactate efflux, it should be kept in mind that lactate efflux will itself counteract the imposed extracellular alkalosis by causing the 'K' values to change in the extracellular pool when the lactate enters this pool; (b) [H+] is apparently unlikely to be involved in muscle fatigue development within muscle cells, so its export (if this occurs) is likely irrelevant to muscle function, and most importantly (c) It is unlikely that increased intracellular or extracellular [lactate-] is deleterious to exercise performance (DRAKE et al., 1980; MENGUAL et al., 2003; NIELSEN et al., 2001; PHILP et al., 2005; SAMAJA et al., 1999; SUMIDA et al., 2006; VAN MONTFOORT et al., 2004). As described earlier however, some research groups have indeed noted performance improvements coincident with sodium bicarbonate ingestion or infusion to the blood, while others have not. Relatively large fluxes in ions such as K+, Na+, Cl-, and lactate- across the sarcolemma of working muscles have been recently implicated in fatigue processes, via effects on the excitability of the muscle membranes, and fluid shifts associated with changes in [ions] across the sarcolemmae (SOSTARIC et al., 2006). The ions deemed most mechanistically important are Na+ and K+ as exercise induces Na+ influx and K+ efflux from the muscle cell (SOSTARIC et al., 2006). An accumulation of extra-cellular K+ has been shown to reduce muscle excitability (SOSTARIC et al., 2006), while Na+ counters the effect of increased extra-cellular [K+], and may ameliorate osmotic perturbation (i.e. muscle cells becoming engorged with water because of Na+ influx. As alluded to above, when the paradigms outlined herein are applied, the hypothesised ergogenic aid is the Na+, the affect of which appears to be maximised when administered with the anion bicarbonate; as opposed to with the anions Cl-, citrate-, or lactate- (VAN MONTFOORT et al., 2004). The proposed ergogenic mechanism (where one exists), rather than a moderation of [H+], is hypothesised by the current author to be an amelioration of fluid and ionic disturbances to homeostasis.

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