Exercise and stress: impact on adaptive processes involving water and electrolytes

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Abstract

The horse has a regulatory system which responds in a complex manner to stress, such as exercise. It supplies the fuel and ensures thermoregulation, resulting in the production of sweat. Cutaneous water and electrolyte losses are controlled by thermoregulation, independent of hydration status and/or electrolyte homeostasis. The negative balance for water Na, K and Cl may be a factor in limiting performance and impairing recovery. The strategy in caring for a horse before, during and after exercise involves improving hydration and electrolyte status and the use of NaCl as a feed or in a watery solution (iso- or hypotonic). The voluntary intake of saline is not safe for any horse. If salt is supplemented in a feed, it is essential that water be made available ad libitum. It is also important that, after salt intake, sufficient time is allowed to give the horse the opportunity to drink an adequate quantity of water. Application of K prior to exercise is not recommended. During exercise, NaCl solutions can be administered, while salty supplements are less suitable as regard the time required to stimulate water intake. After exercise, K can be added to supplements or solutions to balance the K deficit.

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Keywords: Horse; Exercise; Stress; Water; Electrolytes; Supplement

1. Introduction

The widespread exploitation of equines reflects a general principle for the survival of all species, i.e., the capacity to react to external influences by adaptation. In this context, a key factor is the equine’s ability (as in other species) to recognize the condition as a trigger for such processes—this is usually referred to as “stress response.” This implies that any kind of stress stimulates the same response system in the organism. If, for example, we consider the capacity to liberate catecholamines and cortisol, there is obviously a common response, but the real regulating system in the background is the hypothalamus–pituitary–adrenal axis. This system enables the organism to react quite differently depending on the specific kind of stress. Exercise is just such a stressor; enforced circulation, energy mobilization and maintaining constant body temperature require sensors in a regulatory system to formulate the appropriate response, e.g., in the form of lactate or sweat production. Even if specific phenomena, such as sweat composition, are discussed, it should be taken

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2. General reactions to stressful conditions

Several reviews have examined the endocrine system in the exercising horse in comparison to the inactive animal (Hinchcliff, 1998). Therefore, a condensed version on this aspect of exercise is presented here. As shown in Fig. 1, various conditions, which upset the current metabolic balance, induce an endocrine response. Signals generated by the gastrointestinal tract or central nervous tissue stimulate communication with the pituitary gland. Direct links exist between the hypothalamus and the adrenal gland to control heat load by inducing sweating or to prevent hypoglycemia by mobilizing energy reserves.

Mental stress triggers the hypothalamus–pituitary–adrenal axis very effectively—a phenomenon well described in wild animals—but can result in disease and death mainly due to the associated depression of immune competence. The same principle applies when metabolic stress is induced. Various conditions, including increased energy requirement and reduced

Fig. 1. Overview of the hypothalamus–pituitary–adrenal axis (CRF—corticotropin releasing factor; TRH—thyrotropin-releasing hormone; ADH—antidiuretic hormone; ACTH—adrenocorticotropic hormone; TSH—thyrotropic hormone.
energy supply over a specific time period, are characterized by an increase in blood cortisol levels (Table 1).

Exercise-related activity increases the tonus of the sympathetic nervous system mediated by the catecholamines and adrenocorticotropic hormone (ACTH). In contrast to cortisol, which increases during moderate exercise, changes in circulatory catecholamine levels are only visible during strenuous exercise (Fig. 2). The relationship between work load and catecholamines is demonstrated by the correlation in the dependence of plasma catecholamines on lactate (Snow et al., 1992; McKeever, 1998a,b; Kurosawa et al., 1999; Nagata et al., 1999; Coenen et al., 2001). Catecholamines, however, also reflect the reaction in form of a lowered response to exercise with adaptation to training (Fig. 2).

Changes in blood flow, increased cardiac output and stimulation of sweat production are the initial consequences of catecholamine liberation. The sensitivity of the sweat rate is clearly demonstrated in normal and anhidrotic horses (Marlin et al., 1999a,b). The reduced sweat response to adrenaline infusion in anhidrotic horses explains the significance of catecholamines for the adaptive capacity of equines to workloads involving sweat production.

It is certain that exercise diminish body fluids. A drop in plasma volume is only one indicator of these changes. Hyper (effect of training) or hypovolemia (effect of a single endurance exercise) induce a hormone-driven counteraction, involving renin, aldosterone, vasopressin and others, such as the natriuretic peptide. The effects of exercise, however, can differ as regard sprint vs. endurance run. The change in plasma volume and osmolality is obviously a sensitive mechanism (Masri et al., 1990; McKeever et al., 1991; McKeever, 1998b). A distinct change in osmolality does not occur in all cases; for example, in prolonged exercise, plasma volume decreases while plasma osmolality remains nearly unchanged (Coenen, 1991a).

3. Water and electrolytes: impact of exercise stress or stressful conditions

3.1. General aspects

Table 1

<table>
<thead>
<tr>
<th>Type of metabolic stress</th>
<th>Control conditions</th>
<th>After load</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed withdrawal, 96 h</td>
<td>47</td>
<td>55</td>
<td>Rose and Sampson, 1982</td>
</tr>
<tr>
<td>Pack horses, transport up to 175 kg</td>
<td>29</td>
<td>54</td>
<td>Coenen et al., 1999b</td>
</tr>
<tr>
<td>Penned, no water, 32 h</td>
<td>80</td>
<td>170</td>
<td>Friend, 2000</td>
</tr>
<tr>
<td>Transported and watered, 32 h</td>
<td>80</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>Transported, no water, 32 h</td>
<td>75</td>
<td>110</td>
<td></td>
</tr>
<tr>
<td>Jumping</td>
<td>60</td>
<td>130</td>
<td>Linden et al., 1991; levels</td>
</tr>
<tr>
<td>Cross-country ride</td>
<td>95</td>
<td>155</td>
<td>1991; levels</td>
</tr>
<tr>
<td>Trotting race</td>
<td>100</td>
<td>190</td>
<td>taken from</td>
</tr>
<tr>
<td>Flat race</td>
<td>80</td>
<td>170</td>
<td>figure</td>
</tr>
<tr>
<td>Distance ride</td>
<td>95</td>
<td>260</td>
<td></td>
</tr>
<tr>
<td>Incremental exercise test</td>
<td>21</td>
<td>30</td>
<td>Nagata et al., 1999</td>
</tr>
<tr>
<td>Workload at 105% of VO_{max}</td>
<td>20</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>6 Consecutive sprints, 1 min, 7 m/s, high fat diet</td>
<td>87</td>
<td>114</td>
<td>Graham-Thiers et al., 2001</td>
</tr>
<tr>
<td>Identical but low fat diet</td>
<td>58</td>
<td>83</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2. Adrenalin in plasma of trotters in dependance on speed and training status (Coenen et al., 2001).
of water and electrolytes is counteracted in the horse by excretion, via feces and, chiefly, urine, to keep the balance within a neutral range. As shown in Fig. 3, renal excretion of water and electrolytes is the only dependent variable which reflects differences in intake and/or additional output via sweat (or diarrhea). Excretion through sweat itself depends solely on the duration and intensity of exercise and on environmental conditions but not on intake. Extrarenal tissues—e.g., the extracellular space—can be stressed by temporary depletion if reduced renal excretion does not balance sweat loss. The gastrointestinal tract (GIT) can be involved as a temporary reservoir; as regard this function, its capacity depends on diet and the time between feeding and exercise. Intake, absorption and fecal and renal excretion are in a steady state; the balance is zero after a certain time, but as soon as exercise begins, the balance drops immediately and becomes negative in proportion to sweat loss. This is dictated by the fundamentals of thermoregulation.

3.2. Water

Body fluid volumes are well regulated (Fig. 1) but can change of course in response on training and exercise (Persson, 1967; McKeever et al., 1991). Total body water is estimated at 662 ml/kg BW (Table 2).

In equines, the figures for water distribution are similar to those in other species; however, extracellular space, which includes plasma volume, varies between breeds. A large variation is also found for water fixed in the GIT and depends on the type of feed and the amount of roughage in the ration (Meyer, 1996a,b,c). Water intake reflects the following demands:

- secretion into the GIT;
- transport of dry matter through the GIT;
- dissolution of absorbed nutrients and transport to certain tissues;
- dissolution of substances for renal elimination;
- maintenance of body water space; and
- export of heat via sweat and expiration.

The water intake to cover these needs depends on the dry matter of feed, water holding capacity, feed composition and the environment. Wild horses (Equus przewalskii; ~300 kg BW) consume between 1 and >20 l/day, the main influence being environmental temperature (Fig. 4; Fritsch, 1998).

Up to about 15 °C, water intake varies for this type of horse by about 2 l/day (~7 ml/kg BW); rain influences water intake associated with feed, but in general, this effect seems to be small compared to the dominating role of temperature. At about 20 °C, water intake reaches 20 ml/kg BW. Johnson (1998) assumes a daily water consumption rate of 25–80 ml/kg BW. For stabled horses, Meyer et al. (1990a) measured a daily water intake of 40–75 ml/kg BW. In relation to dry matter (DM) intake, water consumption in horses fed hay and concentrates will vary between 2.5 and 3.5 l/kg DM (according to Warren et al., 1999).

After feeding and watering, a positive water balance is achieved (Fig. 5); water retention increases postprandially for approximately 4–5 h and begins to decline thereafter. A period of exercise changes water

<table>
<thead>
<tr>
<th>Compartment</th>
<th>ml/kg BW</th>
<th>n</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total body (TBW)</td>
<td>662</td>
<td>108</td>
<td>Tritium</td>
</tr>
<tr>
<td>Extracellular space (ECW)</td>
<td>239</td>
<td>128</td>
<td>Thiocyanate</td>
</tr>
<tr>
<td>Plasma volume (PV)</td>
<td>52</td>
<td>163</td>
<td>Evans blue</td>
</tr>
<tr>
<td>Extravascular part of ECW (ECWev)</td>
<td>187</td>
<td></td>
<td>ECW-PV</td>
</tr>
<tr>
<td>Gastrointestinal tract (GITw)</td>
<td>132</td>
<td>38</td>
<td>Direct weight/slaughtered horses</td>
</tr>
<tr>
<td>Intracellular space</td>
<td>291</td>
<td></td>
<td>TBW−(ECW+GITw)</td>
</tr>
</tbody>
</table>
retention dramatically; although there is a decrease in renal water excretion, the rate of fluid loss through sweating during a 2-h exercise period results in a negative water balance. Limited water intake primarily reduces the amount of water in the GIT (Peters, 1994). A diet low in fiber and feed withdrawal for 12 h have comparable consequences (Coenen et al., 1990; Coenen, 1991a; Meyer, 1996a). The degree to which the GIT contributes to the compensation of exercise-related fluid losses, as estimated in various studies (Meyer, 1996a,b,c), has not been clearly defined. This lack of precise information is possibly related to the sensitivity of the techniques used.

Feeding fibrous diets with large amounts of beet pulp may increase water consumption and plasma volume. Furosemide treatment, which was used to simulate water losses during exercise in horses (Warren et al., 1999), induced a greater loss in body weight after ingestion of a diet rich in pectin and a similar decrease in plasma volume, compared with a diet low in total fiber and low in soluble fiber (pectin). This ‘fiber effect’ is obviously reduced if a typical source of roughage is fed instead of the highly fermentable pectin from beet pulp. Feeding hay corresponded to a higher water intake compared with a hay-grain diet (Pagan and Harris, 1999) but failed to create positive effects on plasma volume.

Sweat production has the greatest influence on water balance and, consequently, on water intake. As sweat volume varies in relation to exercise conditions, the influence of exercise on sweat production cannot be quantified simply. Depending on exercise intensity and the environment, the sweat rate varies between 10 and more than 35 ml/m²/min (Meyer et al., 1990b; McCutcheon and Geor, 1998). Exercise-related heat production generally determines the sweat rate. Heat production by the exercising horse depends on total metabolic power (Jones and Carlson, 1995), which is composed of the mass-specific aerobic power (related to oxygen uptake) and the net anaerobic power (lactate accumulation). The metabolic power dictates the increase in body temperature as reflected by the change in pulmonary arterial blood temperature and heat accumulation (Fig. 6). As metabolic power reflects the energy expenditure per unit of time, heat production can be estimated assuming that 80% of energy is converted to heat. Sophisticated models describe the routes of heat energy by convection, radiation, conduction and evaporation (Mostert et al., 1996).

Neglecting the less significant modes of heat transportation out of the system and assuming that the latent heat of H₂O vaporization is 2428 kJ/l for sweat, calculating 80% of total metabolic power (energy converted to heat) divided by 2428 delivers a rough impression of the necessary sweat volume and sweat rate, respectively. The ability to transfer remarkably large amounts of heat is essential for the maintenance of working capacity and depends on environmental temperatures and humidity (Marlin et al., 1996; Mostert et al., 1996; Jeffcott and Kohn, 1999). In particular, high humidity reduces the
efficiency of evaporation and, thus, reduces heat export via sweat (Fig. 7; Mostert et al., 1996). In monitoring the complex environmental conditions before and during a competition, the combined measurement of humidity and temperature—expressed as a ‘wet bulb globe temperature index’—specifically recognizes the impact of high humidity on the body’s capacity for evaporative energy and is an effective tool in preventing critical heat loads in exercising horses (Schroter et al., 1996).

As regard to the variations in workload, on the one hand, and the complex influence of the environment on cutaneous heat export, on the other, average figures for sweat volume or sweat rate are of limited value. Sweat losses, however, account for ~90% of differences in body weight during exercise (Meyer et al., 1990b). As the dry matter of the body remains nearly unchanged, it can be assumed that the conductivity of body mass varies prior to and after exercise; this, in principle, can be measured using the impedance measurement technique (Adkins, 1996; Bartholomeussen, 1996). This technique is well established in human sports mainly to estimate body fat. Using 5 or 200 kHz (Equistat®), it is possible to estimate the fluid compartments in the horse. Furthermore, there are differences in the impedance before and after exercise, but their relation to changes in body weight due to sweating requires experimental work to establish a model for the calculation of body fluids in exercised horses via impedance measurement. For practical purposes, therefore, the change in body weight must be taken as an indicator for sweat. Taking a certain range of sweat rates (Table 3) into account results in body water losses of up to 6.5% and even more under difficult conditions.

### 3.3. Electrolytes

Exercise induces remarkable changes in the internal balance of several substances, such as glycogen, fat or even calcium (Ca). The drop in ionized Ca and

<table>
<thead>
<tr>
<th>Sweat rate (ml/kg BW)</th>
<th>Total sweat l/horse</th>
<th>Percent of TBW</th>
<th>Heat export via evaporation (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>5.5</td>
<td>1.6</td>
<td>13,354</td>
</tr>
<tr>
<td>20</td>
<td>11.0</td>
<td>3.2</td>
<td>26,708</td>
</tr>
<tr>
<td>30</td>
<td>16.5</td>
<td>4.8</td>
<td>40,062</td>
</tr>
<tr>
<td>40</td>
<td>22.0</td>
<td>6.5</td>
<td>53,416</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Major constituents (g/l)</th>
<th>Minor constituents (g/l)</th>
<th>Traces (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na 2.8</td>
<td>Ca 0.12</td>
<td>Cu 0.3</td>
</tr>
<tr>
<td>K 1.4</td>
<td>Mg 0.05</td>
<td>Zn 11.4</td>
</tr>
<tr>
<td>Cl 5.3</td>
<td>P &lt;0.01</td>
<td>Mn 0.16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Se &lt;0.005</td>
</tr>
</tbody>
</table>
resultant secretion of parathyroid hormone (PTH) is an example (Vervuert et al., 2002) of a reaction in the range of exercise responses. They do not, however, necessarily (e.g., Ca) change the external balance to a greater degree. Therefore, the influence of exercise on requirements for Ca is low.

The acknowledged figures (Table 4) elucidate that cutaneous losses, other than for sodium (Na), potassium (K) and chloride (Cl), can be neglected as a factor for the external balance (Meyer, 1987; McCutcheon et al., 1995; McCutcheon and Geor, 1998).

The daily maintenance requirement for Na in a 550-kg horse is calculated to be ~11 g (Table 5). Considering a dry matter (DM) intake of 10 kg/day, it needs, on average, ~1 g Na/kg DM. Many types of roughage contain less than 1 g/kg DM. Therefore, if a horse exercises, original Na contents of feeds are not sufficient to cover the increased requirement. Fecal excretion is less variable compared to renal Na output, which correlates with Na intake. A remarkably high proportion of Na is stored in the skeleton (Table 6).

Chloride is distributed among several tissue types which contain >15% of total body Cl. Recently ingested portions of Na and Cl are stored in the GIT, which again qualifies the GIT as a temporary reservoir.

Information on external balance of specified electrolytes is extensive. This includes the fact that, within a short time the exercising, a horse will lose about 8%, 3% and 20% of total body Na, K and Cl, respectively (Table 7). A comparison of these amounts with those in horses suffering from diarrhea (Schott, 1998) underlines the fact that only a completely healthy horse can tolerate such high water and electrolyte loss rates.

Normally, potassium intake greatly exceeds requirements due to the K concentrations in most types of roughage (>15 g/kg DM). Muscle tissue contains about three quarters of total body K.

Anhidrosis, diarrhea, renal disease, hypocalcaemia and hyperkalaemia are conditions associated with an altered electrolyte status. They limit the utilization of a horse’s genetically determined exercise capacity (Marlin et al., 1996, 1999a,b; Valberg et al., 1999; McCutcheon et al., 1999). Keeping a healthy horse in peak condition requires:

→ internal pathways for temporary compensation of a negative electrolyte balance and
→ a specific feeding regime to balance cutaneous water and electrolyte losses.

Table 5
Basic figures for electrolyte requirements (GEH, 1994)

<table>
<thead>
<tr>
<th>Element</th>
<th>Endogenous losses (mg/kg BWxd⁻¹)</th>
<th>Utilization (%)</th>
<th>Requirement maintenance (mg/kg BWxd⁻¹)</th>
<th>Requirement for exercise (g/l sweat)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na</td>
<td>18</td>
<td>90</td>
<td>20 (11)*</td>
<td>3.1</td>
</tr>
<tr>
<td>K</td>
<td>40</td>
<td>80</td>
<td>50 (27.5)</td>
<td>1.6</td>
</tr>
<tr>
<td>Cl</td>
<td>5</td>
<td>100</td>
<td>80 (44)**</td>
<td>5.5</td>
</tr>
</tbody>
</table>

* In brackets—requirement for a 550-kg horse, g/day.

** Factorial approach not suitable for Cl due to impact on acid base balance if fed according to endogenous losses (Coenen, 1999).

Table 6
Total body electrolytes and their distribution in various tissues (Lindner, 1983; Gürer, 1985; Meyer, 1987; Coenen et al., 1990; Coenen, 1991a)

<table>
<thead>
<tr>
<th>Sodium</th>
<th>Potassium</th>
<th>Chloride</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entire body mass</td>
<td>1580</td>
<td>2090</td>
</tr>
</tbody>
</table>

Partitions of several tissues (%)

| Muscle | 10.8 | 75.1 | 19.9 |
| Ingesta | 12.4 | 4.5 | 14.1 |
| Blood | 10.8 | 2.4 | 15.5 |
| Skin | 8.5 | 2.6 | 15.1 |
| GIT tissue | 4.3 | 5.6 | 6.1 |
| Other organs | 2.1 | 5.0 | 15.4 |
| Skeleton | 51.1 | 4.7 | 13.9 |

Table 7
Calculated losses of electrolytes via sweat at different sweat rates

<table>
<thead>
<tr>
<th>Sweat rate (ml/kg BW)</th>
<th>Cutaneous losses (mg/kg BW)</th>
<th>Cutaneous losses in percent of total body store</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Na</td>
<td>K</td>
</tr>
<tr>
<td>10</td>
<td>31</td>
<td>16</td>
</tr>
<tr>
<td>20</td>
<td>62</td>
<td>32</td>
</tr>
<tr>
<td>30</td>
<td>93</td>
<td>48</td>
</tr>
<tr>
<td>40</td>
<td>124</td>
<td>64</td>
</tr>
</tbody>
</table>

→ internal pathways for temporary compensation of a negative electrolyte balance and
→ a specific feeding regime to balance cutaneous water and electrolyte losses.
4. Can the horse regulate sweat rate and sweat composition to limit the negative balance?

Sweat losses are inevitable; they are outside the control of any regulating influence except the demand for thermoregulation. This has long been acknowledged and demonstrated by the clear relationship between work intensity and sweat rates in various skin regions (Marlin et al., 1996, 1999a,b).

Interestingly, the sensitivity of sweat response decreases in relation to the increase in pulmonary artery temperature (sweat rate sensitivity $g^{-1}m^{-2}min^{-1}$ per °C) from about 18 to ~3 at the neck and from 9 to ~1 in the gluteal region if the work load increases from moderate to strenuous. Obviously, this is a consequence of the altered distribution of blood flow away from the skin towards the exercising muscle (Marlin et al., 1999a). This reaction is not the result of an adaption to retain water and electrolytes, it reflects the inability to keep sweat production in balance with the need for successful thermoregulation. Even in a state of Na, K or Cl depletion with the corresponding lowered electrolyte homeostasis, kidney and metabolic consequences, the electrolyte concentrations in sweat remain unchanged (Fig. 8; Coenen, 1991a). That clearly means the sweat glands cannot (or need not) react to the electrolyte status.

The consequence is a change in electrolyte homeostasis depending on cutaneous losses. To balance these cutaneous losses internally, the horse has the following metabolic tools:

→ enforced absorption from the GIT;
→ reduced renal output; and
→ liberation of electrolytes from certain tissues.

The amounts of water and electrolytes in the GIT are influenced by the type of diet and are obviously reduced in response to exercise (Meyer, 1996a,b,c; Warren et al., 1999). Even if the effect of different dry matter intake is excluded, there still remains an exercise-related uptake of water, Na and Cl but not of K. The conclusion is that the GIT does indeed serve as a reservoir. Consequently, the fact that the amounts of water and electrolytes fixed in the GIT depend on fiber intake (Fig. 9) encourages the conclusion that increased roughage consumption—normally hay—could enforce the reservoir function of the GIT. Kronfeld (2001b) criticized the “reservoir hypothesis,” taking into consideration the additional load created by extra hay intake, the role of high concentrations of short-chain fatty acids in the hindgut, the heat load caused by fermentation and, finally, the elevated fecal water output. In his paper, Kronfeld (2001b) emphasizes the advantage of a low-protein, high-fat diet (for stabled horses) containing slowly fermentable fiber (Graham-Thiers et al., 2001). That ration consists of 40% orchard grass hay, 20% oat straw and a total 40% other feeds, such as cereals and oil. Assuming a dry matter intake for an intensively exercising horse of 2.2 kg/100 kg BW/day, the specified diet would result in a daily

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**Fig. 8.** Electrolyte concentrations in sweat and blood plasma in controls and after depleting horses over several weeks (Lindner, 1983; Gürer, 1985; Meyer, 1987; Coenen, 1991a).

**Fig. 9.** Water in GIT in relation to crude fiber intake (Meyer, 1996a).
roughage intake of ~1.3 kg/100 kg BW. This is in fact within the same range as the German recommendation of 1–1.2 kg roughage/100 kg BW/day. The integrated examination of roughage, as well as fermentation in the large intestine in the exercising horse, underlines the importance of fiber quality by differentiating between carbohydrate fractions with regard to the end products of fermentation (Hoffman et al., 2001; Kronfeld, 2001b)—surely a more important aspect than simply the amount of fiber. The role of heat production by microbial breakdown of carbohydrates seems questionable, however. In ruminants, the heat produced by ruminal fermentation is set at ~4% of gross energy, and the proportion of acetic acid seems to have only a minor effect in altering heat production (Czerkawski, 1980; Orskov et al., 1991). Assuming that the heat liberated by fermentation in the equine hindgut is less than in the rumen, a remarkable change of microbial activity might be a disadvantage, posing the risk of destabilizing the intestinal microflora. To allow the gut to perform the function described above, a limit to lactic acid production is necessary (a matter of feed treatment, such as extrusion and feed distribution over several meals; max. 0.5 kg concentrate/100 kg BW per meal combined with a hay cut just prior to bloom). The role of specific fibrous feeds, such as soy bean hulls or pectin carriers like sugar beet pulp, are of interest in modifying the proportion of rapidly fermentable fiber (Moore-Colyer and Longland, 2001). Nevertheless, this is still an area for experimental work as regard much-needed guidelines for incorporating these compounds into a ration.

Whatever the GIT can yield, the balance during and after exercise remains negative. The kidney may reduce water, Na and Cl excretion (Schott et al., 1991; McKeever, 1998b), but that cannot compensate for cutaneous losses. As shown for Cl, renal excretion is remarkably reduced, but renal and cutaneous losses still exceed intake. In addition, it takes more than 1 day to return to the level of renal output which existed prior to exercise (Fig. 10). This corresponds with protracted fluid losses and their homeostatic effect, following endurance tests (Andrews et al., 1995). The limited renal compensation of sweat losses may possibly be further depressed through a high intake of nitrogen and calcium, as they provoke excretion via urine.

As regard K balance, the kidney works counterproductively. As a result of the significant transfer of K from the intracellular to the extracellular space, renal excretion increases in reaction to exercise and, thus, adds to the K deficit (Meyer, 1987; Schott et al., 1991; Johnson, 1998). The dynamic of the changes in K distribution is often overlooked, and analyses before and after exercise may lead to misinterpretations (Kronfeld, 2001a; Harris and Snow, 1992). Soon after beginning exercise, an increase in plasma K occurs, indicating the movement of K from the intracellular towards the extracellular space (Fig. 11). The sweat-related load of K balance is not reflected by plasma concentrations during or immediately after exercise; the measurement of K concentration in plasma, at a specific time after exercise, delivers more information on this notion.

The third element in handling ongoing sweat losses is tolerance against a temporary depletion of the organism in general (in the case of water) or of certain tissues. The water deficit manifests itself in a reduction of plasma volume and extracellular space. As the hypertonic equine sweat induces hypotonic dehydration, there is a counteracting influx of fluid into the cells (Kronfeld, 2001a); therefore, water export is amplified by a change in water distribution. When does a water deficit become dangerous? The increase in blood viscosity and other hematological changes during exercise (Weiss et al., 1996; Fedde and Erickson, 1998; McKeever, 1998a; Funkquist et al., 2001) could prompt the assumption that high sweat losses and, consequently, high water deficits create problems in circulation. The volume itself
seems to be less important, as long as there is no additional heat storage as a result of decreased fluid volume (Geor and McCutcheon, 1998; Kronfeld, 2001a,b,c). Because water loss via sweat and electrolyte load, as well as energy turnover, form a complex partnership, a single figure regarding a tolerable volume deficit is of limited value.

The elimination of electrolytes from body stores during exercise has not been clarified precisely. It can be concluded from depletion experiments that Na levels vary with the fluids, namely, plasma volume and extracellular water space. Muscle tissue is additionally involved (Meyer, 1987). In experimentally induced K deficits, a reduction of K in bone occurs (Gürer, 1985). It is not clear whether this takes place during or after exercise to compensate for enforced K excretion. Cl again follows water and Na; Cl concentrations are reduced in several tissues by exercise (Coenen, 1999) but, interestingly, not in muscle. Here, there is a strong association with Na (Na=25.83+61.58 Cl; r=0.88; mmol/kg muscle DM; Coenen, 1991a). During exercise, the Cl concentration in muscle increases obviously due to an increase of the intracellular portion of Cl. Some studies on other species suggest that a change in intracellular ion balance and—focused on Cl—slightly elevated intracellular Cl levels in muscle play a role in limited performance or fatigue (Lindinger and Heigenhauser, 1988, 1991). Based on our results in ponies, the portion of Cl shifts towards the intracellular space from 3.7% prior to exercise to ~12.2% thereafter.

Cl is hardly involved in the acid–base balance, which is described in more detail elsewhere (Hyyppä and Pösö, 1998; Kingston and Bayly, 1998; Kronfeld, 2001a). The elimination of CO₂ by expiration depends

Na, mmol/l

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Cl, mmol/l

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K, mmol/l

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<tr>
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<td>306</td>
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</tbody>
</table>

S = start
E = end of exercise

* = number of horses
** = duration of exercise, warm up excluded

Fig. 11. K concentration in the plasma of ponies during a 2-h exercise and a 4-h recovery period (2.5–3 m/s; Coenen, 1991a).

Fig. 12. Electrolytes in plasma at the beginning and end of exercise divided into short and long work loads (summary of data from literature, Coenen and Vervuert, 2003).
on the Cl/HCO₃ exchange. The decrease in venous plasma Cl partly mirrors its increase in arterial blood (Taylor et al., 1995); the latter, as well as the influence of Cl on breathing (at rest), indicates the demand for Cl in maintaining acid–base balance.

Cl deficiency is clearly correlated to metabolic alkalosis, as observed in horses with minimized Cl intake (Coenen, 1988, 1991b) and in other species (Neathery et al., 1981; Blackmon et al., 1984). This principle is still present during exercise; any burden on Cl homeostasis induces an alkalotic effect (Coenen, 1991b).

The different concentrations of electrolytes in sweat result in varying responses to electrolyte homeostasis. Fig. 12 shows the literature data roughly separated into exercise periods with <1 h and longer work loads. Regardless of the duration of exercise, the concentrations of Na and K show no major changes, while the Cl concentration drops.

5. Strategies for the care of the exercising horse

In an opening comment to students on this subject, Professor Hintz said, “Keep the gut happy.” This simply implies the primary role of proper ration planning. Kronfeld (2001a) recommends a ration low in protein—balanced with amino acids—high in fat and containing slowly fermentable fibre. Reducing protein helps to lower the acid load for the exercising horse (Graham-Thiers et al., 2001). The rations these authors used contained ~90-g crude protein mainly from hay and straw. This means protein quality is low if no supplementation with amino acids is implemented. On the other hand, the effect of high- or low-protein diets on performance is small (Miller-Graber et al., 1991; Graham-Thiers et al., 2000). As hay often contains >90-g crude protein, it takes bulky feeds, such as straw, to keep protein within that range. Especially in the case of high fat contents in the diet, a more digestible type of roughage than straw should be chosen to maintain sufficient nutrient delivery to the intestinal microflora even if the protein content of the diet then exceeds requirements.

High levels of fat in the diet are purported to have a number of advantages (Kronfeld et al., 1994, 1998; Kronfeld, 2001a,b,c) for exercising horses. Kronfeld recommends up to 12% fat in the ration for exercising horses in light of muscle glycogen requirements and energetics (Kronfeld et al., 1994, 1998). Experimental data from Kronfeld’s group indicate that such a high level of fat is still safe and highly digestible (Kronfeld et al., 2001). On the other hand, in cecally fistulated horses fed a semipurified diet consisting of grass meal, starch, sugar and up to 11% soy bean oil, the fat concentration in ileal chyme reached ~10% of dry matter; in cases with rapid passage, only slight disturbances in fermentation were observed (Coenen, 1986). Zeyner (2002) reported changes in liver enzymes and lipoprotein fractions after using larger amounts of oil. A basic ration design for high yielding horses with a moderately higher protein concentration compared to the recommended ration includes 6 kg hay up to ~0.5 kg beet pulp or a combination of beet pulp and soy bean hulls up to 1 kg oil and ~4 kg processed grain. This feeding regime delivers about 35% of digestible energy (DE) each from roughage and grain and about 26% of DE from fat. The starch intake will be around 2.5 kg/day or even higher. To maintain this amount within a safe range, the amount of high starch concentrates should not exceed 0.5 kg/100 kg BW per meal; this will keep starch intake per meal below 2 g/kg BW (Meyer et al., 1995).

To date, there is no conclusive evidence that additives, such as niacin or yeast, protect the equine microbial system as they do in ruminants.

A main concern in feeding exercising horses of course is the challenge regarding the water and electrolyte supply (McCutcheon and Geor, 1996; Schott et al., 1998; Dusterdieck et al., 1999). The question relates not so much to requirements, where the data are sufficiently precise, but more to suitable composition, amounts of supplements and the proper time for feeding. The general procedure is to stimulate water intake through electrolyte consumption or to use solutions for application via nasogastric tube. There are only small changes in the osmolarity of body fluids (hypotonic dehydration), and therefore, there is no signal for thirst. Increasing plasma osmolarity by feeding electrolytes stimulates water intake; experiments with a salty supplement showed that the stimulation of water consumption completely covered sweat-related weight losses (Coenen, 1991a; Coenen et al., 1995). Comparable benefits were also observed by Nyman et al. (1996).
and Schott et al. (1999). Application of water alone depresses electrolyte homeostasis, effectively only balancing fluid losses (Hyypää et al., 1996; Schnermann, 2000). While hypertonic preparations should be avoided, iso- or hypotonic electrolyte solutions are suitable; experiments revealed no distinct differences in Na and Cl homeostasis between iso- or hypotonic NaCl solutions (Sosa Leon et al., 1995a; Coenen et al., 1999a).

As the K concentration increases during exercise, an enforced K intake can amplify this reaction and create a definite risk to heart function. That is the reason why Kronfeld (2001c) recommends two types of supplements: one without K for use prior to or during exercise and a second one for feeding after exercise. Table 8 shows the composition of different suitable solutions or feeds. Preloading, as well as supplementation during exercise or thereafter, are investigated, and no evidence is derived to strictly recommend a specific procedure. The only aspect to consider is that salty feeds, prior to exercise, must be given with water. As it takes at minimum ~1 h to achieve an increase in osmolarity, these kinds of supplements should be given about 4 h before exercise, allowing the horse sufficient time to consume additional water.

6. Conclusion

The horse has an enormous capacity to compensate and tolerate a load to the thermoregulatory system. Nevertheless, its reduced capacity to eliminate the heat generated by strenuous exercise is a performance-limiting factor. A basic ration, which depresses the acidic effect of metabolism, lowers heat production itself and decreases cortisol release, could be a successful formula. Besides the use of fat (~25% of total DE), fermentable fiber is needed to at least prevent a collapse of the microbial system in the hindgut. The influence of fiber types on the functioning of intestinal microbes, as well as the horse itself, needs to be examined in more detail. Water and electrolyte metabolism requires a specific supplement to aid the horse in balancing sweat losses. Dry feeds rich in Na and Cl are easy to handle but must be offered on an appropriate time schedule to avoid high salt intake without water.

Table 8
Mixtures or solutions for supplementation of exercising horses

<table>
<thead>
<tr>
<th>Ingredient/units</th>
<th>A (%)</th>
<th>B (%)</th>
<th>C (g)</th>
<th>D (%)</th>
<th>E (mmol/l)</th>
<th>F (%)</th>
<th>G (%)</th>
<th>H (%)</th>
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<td>Sugar beet syrup</td>
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<tr>
<td>NaCl</td>
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<td>13.2</td>
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<td>KCl</td>
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<td>6.8</td>
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<td>CaCl₂</td>
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<td>Cl 31.1</td>
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<td>Glucose</td>
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<tr>
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References 1 2 3 4 5 6 6 7 8 8

(1) Coenen, 1991a; Coenen et al., 1995; (2) Nyman et al., 1996; (3) Hyypää et al., 1996; (4) Jansson et al., 1995; (5) Sosa Leon et al., 1995b, additional phosphate 29, sulphate 10 mmol/l; (6) Schott et al., 1999; (7) Marlin et al., 1998, additional HCO₃⁻ 27, dextrose 30 mmol/l; (8) Kronfeld, 2001b.
References


