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EXERCISE AND STRESS—IMPACT ON ADAPTIVE PROCESSES INVOLVING WATER AND ELECTROLYTES

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Introduction

The widespread use of equines in different situations reflects a simple fact, a general principle for all species which have survived until now: the capacity to react to external influences by adaptation and not by refusal. A key position in this context is the ability of the equine organism–as in other species–to realize a condition as a trigger for such processes; we usually call this "stress response." This implies that any kind of stress stimulates the same principle of answers in the organism. If we take into consideration the capacity to liberate catecholamines and cortisol, there is obviously a common answer, but the real regulating structure in the background is the hypothalamus-pituitary-adrenal axis; this 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 proper answer (e.g., in the form of lactate or sweat production). Even if specific phenomena such as sweat composition are discussed, it should be taken into account that they are parts of a network. Excellent reviews and collections of papers are available concerning fluids and electrolytes in exercising horses, and the author emphasizes that they are essential in delivering complete information reflecting the current state of knowledge (Carlson, 1987; Meyer, 1987; Meyer, 1990; Jeffcott and Clarke, 1995, 1996, 1999; Hinchcliff, 1998; Kronfeld, 2001a, 2001b, 2001c).

General Reactions to Stressful Conditions

As shown in Figure 1, various situations which upset the current balance of metabolism induce an endocrine response. Signals generated by the gastrointestinal tract or central nervous tissues stimulate communication with the pituitary gland. Direct links exist between the hypothalamus and the adrenal gland to manage 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 is present when metabolic stress is induced. Various situations, including increased energy requirement and limited energy supply for a certain period of time, are characterized by an increase in blood cortisol levels (Table 1).

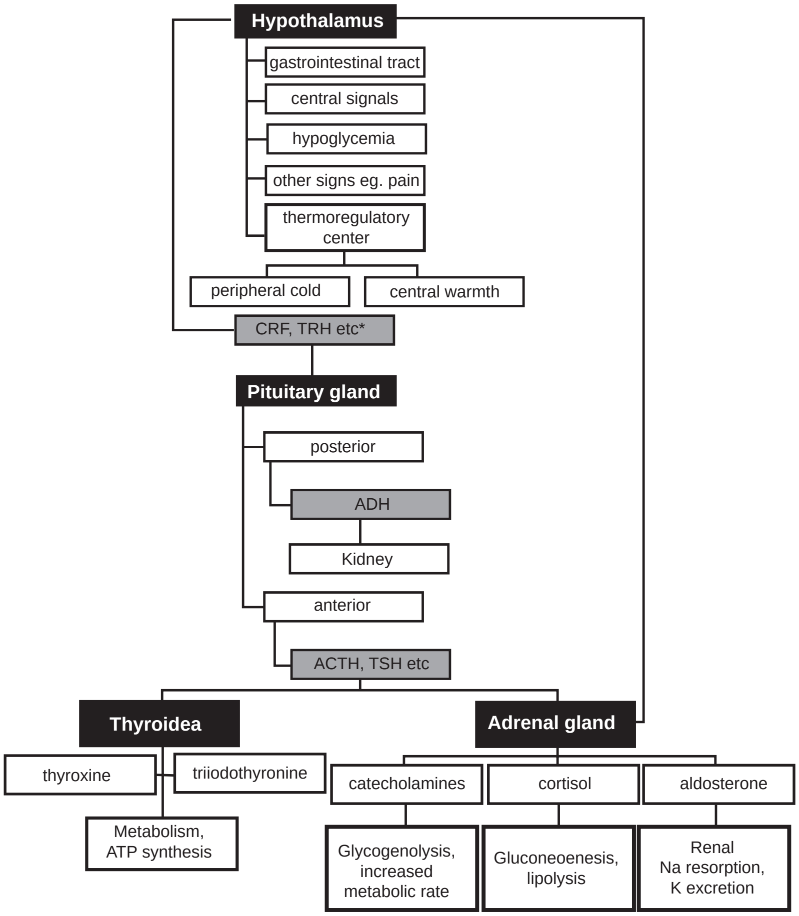

Figure 1. Overview of the hypothalamus-pituitary-adrenal axis (CRF=corticotropin releasing factor; TRH=thyrotropin-releasing hormone; ADH=antidiuretic hormone; ACTH=adrenocorticotropic hormone; TSH= thyrotropic hormone).

Exercise-related activity increases the tonus of the sympathetic nervous system mediated by the catecholamines and ACTH. In contrast to cortisol, which already increases during moderate exercise, changes in circulatory catecholamine levels are only visible during strenuous exercise (Figure 2). The correspondence between workload and catecholamines is demonstrated by the correlation of plasma catecholamines in dependence on lactate (Snow et al., 1992; McKeever 1998;

Table 1. Cortisol in blood plasma (µg/l) of horses under various conditions.

Type of metabolic stress	*Control conditions*	*After load*	*Authors*
Feed withdrawal, 96 h	47	55	Rose and Sampson, 1982
Pack horses, transport uphill, up to 175 kg	29	54	Coenen et al., 1999
Penned, no water, 32 h	80	170	Friend, 2000
Transported and watered, 32 h	80	90	
Transported, no water, 32 h	75	110	
Jumping	60	130	Linden et al., 1991; levels taken from figure
Cross-country ride	95	155	
Trotting race	100	190	
Flat race	80	170	
Distance ride	95	260	
Incremental exercise test	21	30	Nagata et al., 1999
Workload at 105% of VO_{2max}	20	28	
Six consecutive sprints, 1 min, 7 m/s; high fat diet	87	114	Graham-Thiers et al., 2001
Six consecutive sprints, 1 min, 7 m/s; low fat diet	58	83	

Kurosawa et al., 1999; Nagata et al., 1999; Coenen et al., 2001). But the catecholamines also reflect the reaction, meaning the adaptation to training in the form of a lowered reaction to exercise (Figure 2).

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

Water and Electrolytes–Impact of Exercise Stress or Stressful Conditions

GENERAL ASPECTS

Body fluids and the electrolytes sodium (Na), potassium (K), and chloride (Cl) hold a key position in the thermoregulation of sweating animals. The intake of water and electrolytes is counteracted in the balanced horse by excretion via urine (chiefly) and feces to keep the balance in a neutral range. As shown in Figure 3, the renal excretion of water and electrolytes is the only dependent variable which reflects differences in intake and/or additional output via sweat (or diarrhea).

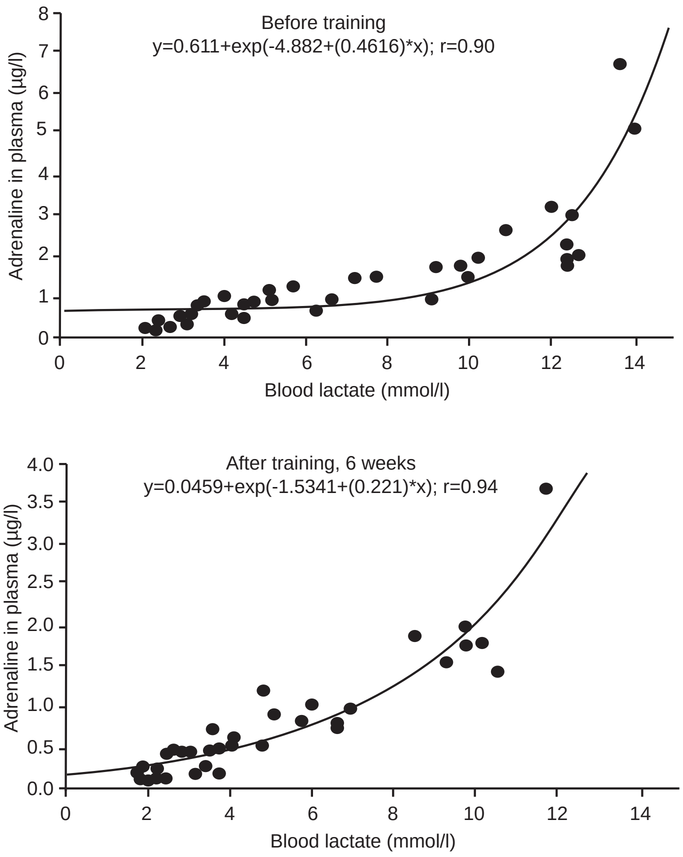

Figure 2. Adrenaline in plasma of trotters in dependance on speed and training status (Coenen et al., 2001)

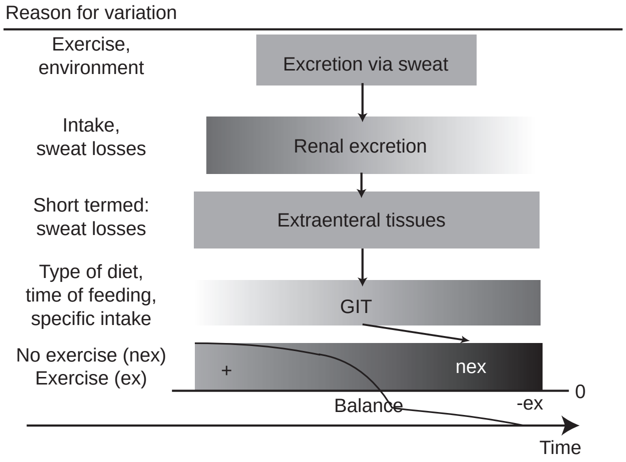

Figure 3. Principle between different compartments exchanging water and electrolytes.

Excretion through sweat itself depends on the duration and intensity of exercise and on environmental conditions, but not on intake. Extraenteral tissues (e.g., 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; regarding that function, its capacity depends on diet and the time between feeding and exercise. Intake, absorption, and fecal and renal excretion are balanced to a steady state. The balance will be at zero after a certain time, but as soon as exercise begins, the balance will drop immediately and turn to the negative side in proportion to sweat losses. This is dictated by thermoregulation.

WATER

Total body water can be estimated at 662 ml/kg BW (Table 2).

Table 2. Fluid volume in the horse (Summary of data from literature).

Compartment	*ml/kg BW*	*n*	*Method*
Total body (TBW)	662	108	Tritium
Extracellular space (ECW)	239	128	Thiocyanate
Plasma volume (PV)	52	163	Evans blue
Extravasal part of ECW (ECWev)	187		ECW-PV
Gastrointestinal tract (GITw)	132	38	Direct weight/slaughtered horses
Intracellular space	291		TBW-(ECW+GITw)

The figures for water distribution are similar to those in other species. The extracellular space includes plasma volume, which varied between breeds. A high variation is also given for water fixed in the GIT, and this depends on the type of feed and the amount of roughage in the ration (Meyer, 1996a; 1996b; 1996c). 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,
- 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 about 1-20 l/day; the main influence is environmental temperature (Figure 4) (Fritsch, 1998).

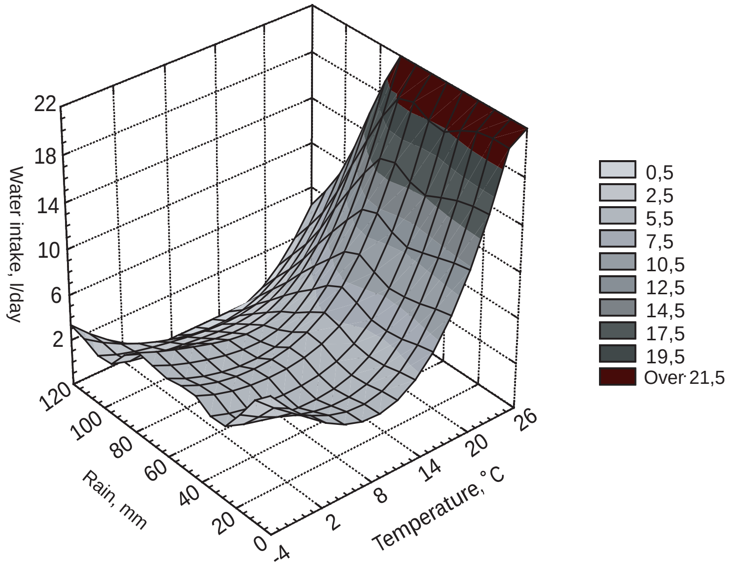

Figure 4. Drinking water intake in *Equus przewalskii* under seminatural conditions (Fritsch, 1998).

At an environmental temperature up to about 15°C, water intake varies for this type of horse at 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 (1990) 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 k/kg DM (Warren et al., 1999).

After feeding and watering, a positive water balance is achieved (Figure 5); water retention increases postprandially for up to about 4-5 hours and begins to decline thereafter. A period of exercise changes water retention dramatically; although there is a decrease in renal water excretion, the rate of fluid loss through sweat during a 2-hour 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 hours have comparable consequences (Coenen et al., 1990; Coenen, 1991; Meyer et al., 1995). It is not well defined to which degree the GIT contributes to the compensation of exercise-related fluid losses as estimated in some cases (Meyer, 1996a, 1996b, 1996c). There is a lack of clear information, possibly related to the sensitivity of the employed methods.

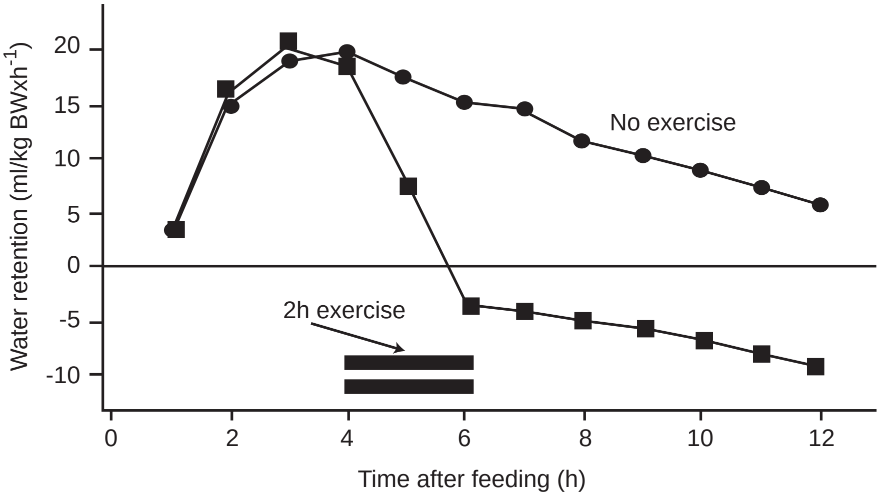

Figure 5. Water retention in horses after ad libitum water availability on days without exercise compared to days with a 2-hour exercise period (Meyer et al., 1990).

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 these 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 to feeding 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 higher water intake compared to 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 in a simple figure. Depending on exercise intensity and the environment, the sweat rate varies between 10 and >35 $ml/m^2 \times min^{-1}$ (Meyer et al., 1990; 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 (Figure 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).

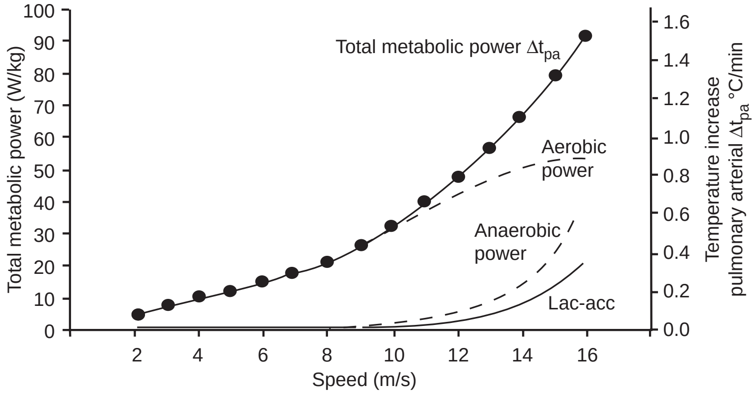

Figure 6. Development of metabolic power in dependence on speed and lactate accumulation and the corresponding increase in body heat indicated by change in temperature of pulmonary arterial blood (Jones and Carlson, 1995).

Neglecting the less significant modes of heat transportation out of the system and assuming that the latent heat of H_2O 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 export remarkably large amounts of heat is essential to maintaining working capacity and depends on environmental temperatures and humidity (Mostert et al., 1996; Jeffcott and Kohn, 1999). Particularly, high humidity reduces the efficiency of evaporation and thus reduces heat export via sweat (Figure 7) (Mostert et al., 1996). In monitoring the complex environmental conditions before and during a competition, the combined measurement of humidity and temperature (expressed in 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).

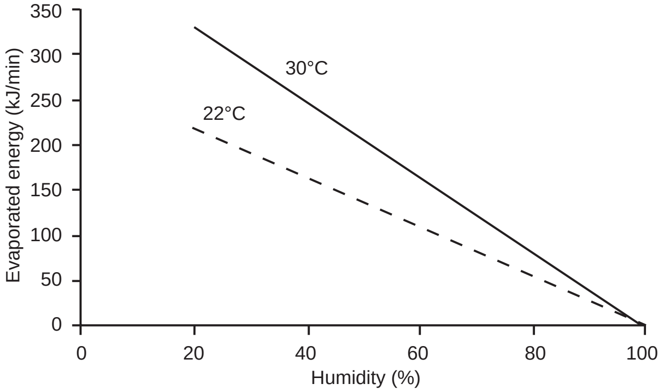

Figure 7. Heat loss via evaporation of sweat during exercise (speed 8.5 m/s) at different temperatures and humidity levels (Mostert et al., 1996).

Regarding 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. However, sweat losses account for ~90% of differences in body weight during the course of exercise (Meyer et al., 1990). 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. This technique is well-established in human sports, mainly to estimate body fat. Using 5 or 200 kHz (Equistat®), it is possible to estimate horses' fluid compartments; 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. So far, for practical purposes, 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.

Table 3. Sweat rate and total sweat volume and corresponding heat evaporation in a 550-kg horse (TBW 620 ml/kg BW).

Sweat rate	*Total sweat*		*Heat export via*
ml/kg BW	*l/horse*	*% of TBW*	*evaporation, kJ*
10	5.5	1.6	13,354
20	11.0	3.2	26,708
30	16.5	4.8	40,062
40	22.0	6.5	53,416

ELECTROLYTES

Exercise induces remarkable changes in the internal balance of several substances such as glycogen, fat, and even calcium (Ca). The drop in ionized Ca, answered by a secretion of parathyroid hormone (PTH), is an example of one of the many reactions in the concert of exercise response (Vervuert et al., 2002). But these reactions do not necessarily (e.g., Ca) change the external balance to a greater degree. Therefore, the influence of exercise on requirements 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 about 11 g (Table 5). Considering a dry matter (DM) intake of 10 kg/day, it needs on average approximately 1 g Na/kg DM. Many types of roughage contain less than 1 g/kg DM. At least 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).

Table 4. Sweat composition (Meyer 1990; McCutcheon and Geor, 1998).

Major constituents (g/l)		*Minor constituents (g/l)*		*Traces (mg/l)*	
				Fe	4.3
Na	2.8	Ca	0.12	Cu	0.3
K	1.4	Mg	0.05	Zn	11.4
Cl	5.3	P	<0.01	Mn	0.16
				Se	<0.005

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

Element	*Endogenous losses mg/kg BWxd-1*	*Utilization %*	*Requirement maintenance mg/kg BWxd-1*	*Requirement for exercise*	
				net, g/l sweat	*total, g/l sweat*
Na	18	90	20 (11)*	3.1	3.44
K	40	80	50 (27.5)	1.6	2.0
Cl	5	100	80 (44)**	5.5	5.5

* 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 the distribution over different tissues (Lindner, 1981; Gürer, 1985; Meyer et al., 1987; Coenen, 1991; Coenen et al., 1991).

	Sodium	*Potassium*	*Chloride*
	total body store, mg/kg BW		
Whole body mass	1580	2090	1124
	partition 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

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. This again qualifies the GIT as a temporary reservoir.

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

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

Sweat rate ml/kg BW	*Cutaneous losses mg/kg BW*			*Cutaneous losses in % of total body storage*		
	Na	*K*	*Cl*	*Na*	*K*	*Cl*
10	31	16	55	2.0	0.8	4.9
20	62	32	110	3.9	1.5	9.8
30	93	48	165	5.9	2.3	14.7
40	124	64	220	7.8	3.1	19.6

The potassium intake normally greatly exceeds requirements due to the potassium concentrations in most types of roughage (>15 g/kg DM). Muscle tissue contains about three-quarters of total body potassium. Anhidrosis, diarrhea, renal disease, hypocalcaemia, and hyperkalemia are conditions that limit the utilization of a horse's genetically determined exercise capacity (Marlin et al., 1999; McCutcheon et al., 1999; Valberg et al., 1999). Keeping a healthy horse in a high-yielding status requires:

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

Can the Horse Regulate Sweat Rate and Sweat Composition to Limit the Negative Balance?

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

Interestingly, the sensitivity of sweat response decreases in relation to the increase in pulmonary artery temperature (sweat rate sensitivity g/m^{2}xmin-1x°C^{-1}) from about 18 to ~3 at the neck and from 9 to ~1 in the gluteal region if the workload increases from moderate to strenuous, obviously as a consequence of the altered distribution of blood flow away from the skin towards the excercising muscle (Marlin et al., 1999b). This reaction is not the result of an adaptation to retain water and electrolytes; rather, 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 (Figure 8, Coenen, 1991). That clearly means the sweat glands cannot (or need not) react to the electrolyte status.

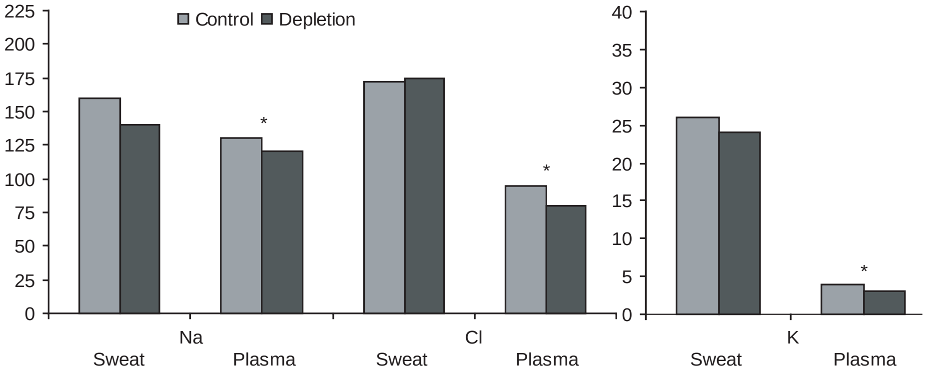

Figure 8. Electrolyte concentrations in sweat and blood plasma in controls and after depleting horses over several weeks (Linder, 1981; Gürer, 1985; Meyer, 1987; Coenen, 1991).

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 reaction to exercise (Meyer, 1990; Warren et al., 1999). Even if the effect of different dry matter intake is excluded, there still remains an exercise-related intake of water, Na, and Cl but not of K. The conclusion from that result is that the GIT indeed serves as a reservoir. The fact that the amounts of water and electrolytes fixed in the GIT depend on fiber intake (Figure 9) consequently encourages the conclusion that increased roughage consumption–normally meaning 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 in 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 x d^{-1}, the specified diet would result in a daily 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 x d^{-1}, although the role of the GIT in temporarily contributing to the compensation of sweat losses is one argument in formulating roughage recommendations. However, the integrated examination of roughage and 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, 2001; Kronfeld, 2001b)–surely a more important aspect than simply the amount of fiber. But the role of heat production by microbial breakdown of carbohydrates seems questionable. 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 reduction 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; maximum of 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 soybean hulls or pectin carriers like sugar beet pulp can be of interest in modifying the proportion of rapidly fermentable fiber (Moore-Colyer and Longland, 2001). But this is an area that deserves further experimental work and much-needed guidelines for incorporating these compounds in a ration.

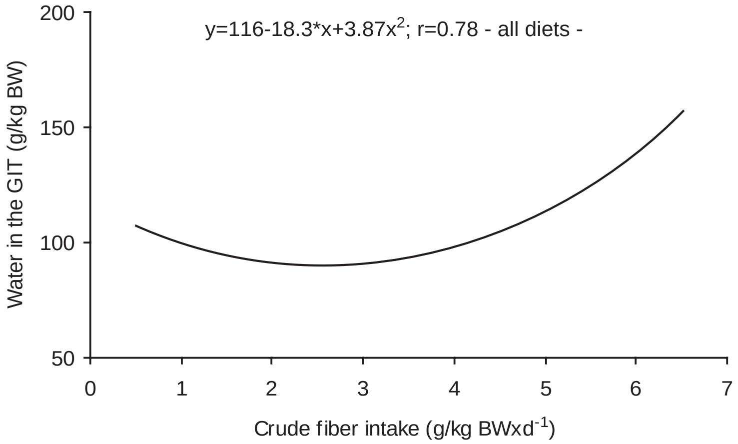

Figure 9. Water in GIT in relation to crude fiber intake (Meyer, 1996a).

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) but cannot compensate cutaneous losses. As shown for Cl, renal excretion is remarkably reduced, but renal and cutaneous losses still exceed intake, and, further, it takes more than one day to return to the level of renal output which existed prior to exercise (Figure 10). This corresponds with the continued fluid losses and their homeostatic effect following the endurance test (Andrews et al., 1995). The limited renal compensation of sweat losses can possibly be further depressed through a high intake of nitrogen and calcium, as they provoke excretion via the urine.

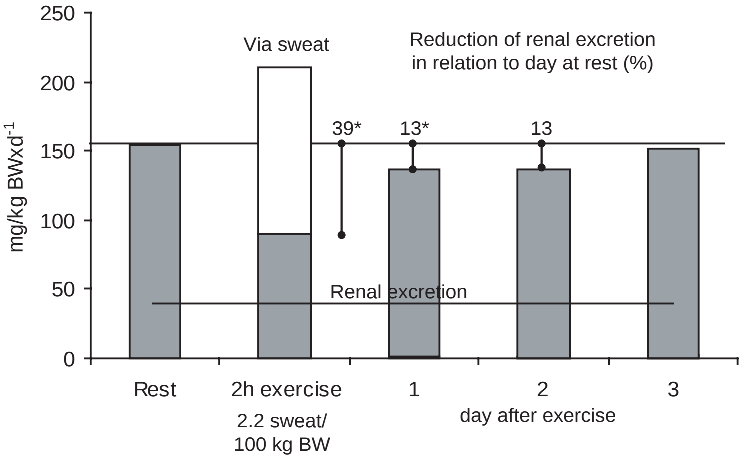

Figure 10. Renal Cl excretion before exercise and the reduction in renal output on the day of exercise and the follow days (Coenen, 1991).

Regarding K balance, the kidney works counterproductively. As a result of the significant transfer of K from the intracellular space to the extracellular space, renal excretion increases in reaction to exercise and thus adds to the K deficit (Meyer, 1987; Schott et al., 1991). 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 the beginning of exercise, an increase in plasma K occurs, indicating the movement of K from the intracellular space towards the extracellular space (Figure 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 a certain time after exercise delivers more information on this aspect.

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. At what degree 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, 1998; 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, 2001b, 2001c). However, because water loss via sweat and electrolyte load as well as energy turnover form a complex concert, a single figure regarding a tolerable volume deficit is of limited value.

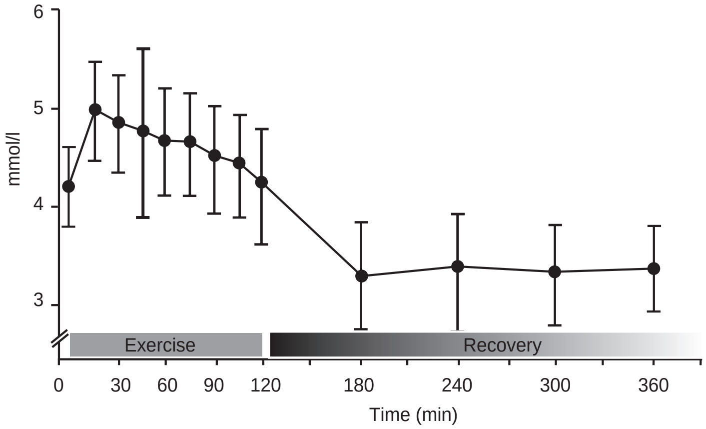

Figure 11. K concentration in the plasma of ponies during a 2-hour exercise and a 4-hour recovery period (2.5-3 m/s) (Coenen, 1991).

The elimination of electrolytes from body stores during exercise is not well-clarified. It can be concluded from depletion experiments that Na levels vary with the fluids, namely plasma volume and extracellular water space. The 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 in order 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, 1991). During exercise the Cl concentration in muscle increases, obviously due to an increase of the intracellular portion of Cl. Some results from studies on other species suggest that slightly elevated intracellular Cl levels in muscle play a role in limited performance or fatigue (Lindinger and Heigenhauser, 1988). Based on our results, in ponies the portion of Cl shifts towards the intracellular space from 37% prior to exercise to ~12.2% thereafter.

Cl is hardly involved in the acid-base balance, which is described in more detail elsewhere (Kronfeld, 2001a; Hyyppä and Poso, 1998; Kingston and Bayly, 1998). The elimination of CO_2 by expiration depends on the Cl/HCO_{3-} 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), indicate 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, 1991) and in other species (Neathery et al., 1991; Blackmon et al., 1984). That principle is still present during exercise; any burden on Cl homeostasis induces an alkalotic effect (Coenen, 1991).

The different concentrations of electrolytes in sweat result in different answers of electrolyte homeostasis. Figure 12 demonstrates data from the literature, roughly separated into exercise periods with <1h and longer workloads. Regardless of the duration of exercise, the concentrations of Na and K show no major changes, while the Cl concentration drops.

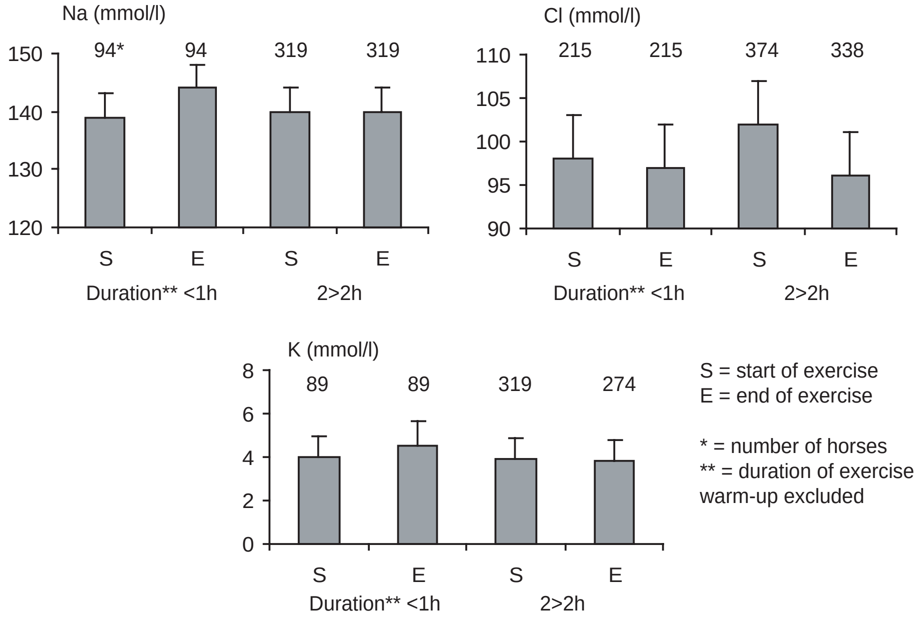

Figure 12. Electrolytes in plasma at start and end of exercise divided in short- and long-lasting workloads (Summary of data from literature).

Strategies in the Care of the Exercising Horse

In an opening comment to students on this aspect, Harold Hintz expressed, “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 fiber. Reducing protein helps to lower the acidic 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. But especially in the case of high fat 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, 1998, 2001a, 2001b, 2001c) for exercising horses. Kronfeld et al. recommend up to 12% in the ration for exercising horses in light of muscle glycogen and energetics (1994, 1998). Experimental data from Kronfeld's group indicate that such a high level of fat is still safe (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% soybean oil, the fat concentration in ileal chyme reached up to 10% of dry matter; in cases with rapid passage, only slight disturbances in fermentation were observed (Coenen, 1986). Zeyner (2001) 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 recommendation above includes 6 kg hay, up to ~0.5 kg beet pulp or a combination of beet pulp and soybean hulls, up to 1 kg oil, and ~4 kg processed grain; this feeding concept 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 keep that 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. The question relates not so much to requirements, as these 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; our experiments with a salty supplement showed that the stimulation of water consumption completely covered sweat-related weight losses (Coenen, 1991); comparable benefits were observed by Nyman et al. (1996) and Schott et al.

(1999). Application of water alone depresses electrolyte homeostasis, effectively only balancing fluid losses (Hyyppä et al., 1996; Schnermann, 2000). While hypertonic preparations should be avoided, iso- or hypotonic electrolyte solutions are suitable; our experiments revealed no distinct differences in the correction of Na and Cl homeostasis between iso- or hypotonic NaCl solutions (Coenen et al., 1999). Sosa Leon et al. (1995) confirmed the suitability of hypotonic preparations.

Table 8. Mixtures or solutions for supplementation of exercising horses.

Ingredient/units	*1*	*2*	*3*	*4*	*3*	*4*	*5*	*6*	*7*	*8*
	%	*%*	*g*	*%*	*mmol/l*	*%*	*%*	*mmol/l*	*%*	*%*
Grass meal	47.6									
Sugar beet syrup	33.3									
NaCl	19.1	100	Na 20.2	100		13.2	13.2		88.2	21.1
KCl			K 9			6.8	6.8			8.3
$CaCl_2$			Cl 31.1						6.9	1.8
$MgCl_2$									4.4	1.2
NaH_2PO_4									0.5	0.14
Glucose										67.4
Glycerol							80			
Commercial product					Na 70, Cl 72, K 31, mmol/l			Na 117, K 40, Cl 130 mmol/l		
Water	free choice	free choice	8.2	10 l, 0.9 % NaCl	17.5 l	80		6 l	free choice ?	free choice ?
Time of supplementation	during/ after	before/ during	after	before	before	before/ during	before/ during	after	before/ during	after only
Ref.	1	2	3	4	5	6	6	7	8	8

1) Coenen et al.,1995; 2) Nyman et al., 1996; 3) Hyyppä, 1996; 4) Jasson et al., 1996; 5) Sosa León et al., 1996, additional: phosphate 10, sulfate 10 mmol/l; 6) Schott et al., 1999; 7) Marlin et al., 1998, additional HCO_{3^-}, dextrose 30 mmol/l; 8) Kronfeld, 2002.

As the K concentration increases during exercise, an enforced K intake can amplify this reaction and create a certain risk regarding 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 argument 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 hour to achieve an increase in osmolarity, these kinds of supplements should be given about 4 hours before exercise. That allows the horse to consume additional water.

Conclusion

The horse has a high capacity to compensate and to tolerate a load to the thermoregulatory system. But the weakening capacity to eliminate the heat which is produced by strenuous exercise is a performance-limiting factor. A basic ration that depresses the acidic effect of metabolism, lowers heat production itself, and lowers cortisol liberation will be a successful concept. Besides the use of fat (~25% of total DE), fermentable fiber is needed in order to at least prevent a collapse of the microbial system in the hindgut. The influence of fiber types on functioning of intestinal microbes as well as the horse itself needs to be examined in more detail. The water and electrolyte metabolism needs 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 according to an appropriate time schedule to avoid high salt intake without water.

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