CHAPTER 10

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APPENDIX A

AN INTEGRATIVE MODEL FOR PREDICTING THERMAL BALANCE IN THE EXERCISING HORSES

ABSTRACT

A theoretical integrative model was developed to determine the heat balance of horses working in a given environment. This model included the following parameters: metabolic heat gain, solar heat gain, evaporative heat loss due to sweating, respiratory tract heat loss, radiation from the body and heat gain or loss due to convection and conduction.

The model developed in this study includes a unique approach for estimating heat loss via evaporation of sweat from the animal's skin surface. Previous studies modelling evaporative heat dissipation are based on the volume of sweat loss. While it is known that the ambient conditions affect evaporation rate, these effects have not been adequately described. The model assumes a body of water adequately represents the horse's skin surface, and it describes the interaction of that water body with the atmosphere.

It is assumed that sweat has thermodynamic characteristics equivalent to distilled water. Sweat, however, has high electrolyte and protein

concentrations and anecdotal evidence has shown that the thermodynamic characteristics may be significantly affected. Further research is therefore required to confirm these characteristics for equine sweat.

The model describes all factors known to affect the thermal balance of the horse working in a given environment. The relative significance of the various variables on the whole integrative model has been illustrated. The effect of ambient temperature and humidity on the evaporative heat loss, the most significant and critical avenue of heat dissipation, is defined and quantified. The model clearly illustrates how increasing relative humidity limits evaporative heat loss, which can be further compromised when horses exercise on treadmills with no air movement.

LIST OF SYMBOLS AND THE UNITS OF THE CORRESPONDING VARIABLES

A	Surface area (m^2).
A_τ	Area of animal emitting to long wave radiation (m^2).
a_L	Long-wave absorptivity of animal coat (dimensionless).
a_s	Short-wave absorptivity of animal coat (dimensionless).
BW	Body weight of animal (kg).
c_p	Specific heat capacity of air (J/g/°C).
c_{pf}	Specific heat capacity of air at film temperature (J/g/°C).
D	Characteristic diameter of the horse (m).
d	Mean diameter of individual hair (m).
h	Coat thermal conductance ($W/m^2/°C$).
h_c	Heat transfer coefficient at film temperature ($W/m^2/°C$).
$\dot{H}_{cond}$	Heat loss via conduction through the hair coat (J/min).
$\dot{H}_{conv}$	Heat loss via forced convection from surface (J/min).
$\dot{H}_{metab}$	Metabolic heat gain (J/min).
$\dot{H}_{rad}$	Heat loss via radiation from animal (J/min).
$\dot{H}_{resp}$	Respiratory heat loss (J/min).
$\dot{H}_{sweat}$	Heat loss via the evaporation of sweat from the surface (J/min).
$\dot{H}_{solar}$	Solar radiation heat gain (J/min).
$\dot{H}_{total}$	Total heat absorbed by animal (J/min).
k_a	Thermal conductivity of air at film temperature (W/m/°C).
k_c	Thermal conductivity of animal coat (W/m/°C).
La	Latent heat of sweat (kJ/ℓ).
L_i	Long wave irradiance (W/m^2).
ℓ_s	Length of hair (m).
n	Number of hair per unit area of skin ($/m^2$).
Nu	Nusselt number (dimensionless).
Pr	Prandl number (dimensionless).
p	Probability per unit coat depth that a penetrating ray will strike a coat element (m^{-1}).
p_w	Ambient water vapour pressure (kPa).

p_s	Saturated vapour pressure of air (kPa).
p_a	Actual vapour pressure of air (kPa).
Rey	Reynolds number (dimensionless).
r_e	External resistance of animal coat (s/m).
S_i	Short wave irradiance (W/m^2).
t	Coat thickness (m).
T_{air}	Air temperature (°C).
T_e	Expired air temperature (°C).
T_i	Inspired air temperature (°C).
T_s	Coat surface temperature (°C).
T_{skin}	Skin temperature (°C).
u	Air speed ≈ travel speed of horse (m/s).
$\dot{V}_E$	Minute volume of horse (ℓ/min).
$\dot{V}O_2$	Oxygen uptake (mℓ/kg/min).
W_e	Expired water vapour (g/min)
W_i	Inspired water vapour (g/min)
x	Length of horse (m).
ΔT	Change in temperature of animal (°C).
$\Delta \dot{T}$	Rate of change of temperature (°C/min).
ε	Emissivity of coat (dimensionless).
μ	Dynamic viscosity of air (g/s/m).
μ_f	Dynamic viscosity of air at film temperature (g/s/m).
ξ	Convection constant of the airflow ($s^{1/2}/m$).
ρ	Density of air (g/ℓ).
ρc_p	Volumetric specific heat of air ($J/m^3/^oC$).
ρ_f	Density of air at film temperature (g/ℓ).
ρ_{sweat}	Density of sweat (g/ℓ).
σ	Stefan Boltzman constant = 5.67×10^{-8} ($W/m^2/^oC^4$).

INTRODUCTION

The environmental conditions at Atlanta, USA, the site of the 1996 Summer Olympics has generated questions concerning the welfare of the participating horses, particularly from countries with markedly different weather conditions to those expected in Atlanta. To address this, and similar issues concerning thermoregulation in horses, a theoretical integrative model was developed to predict the heat balance of the horse under given weather conditions and exercise intensities.

Thermoregulation is the most important regulation system in the homeothermic animal [73]. The animal must keep its body temperature within a very narrow range (37 - 40 °C) despite extreme variations in its metabolic rate and in environmental conditions [141]. Physical work has the greatest effect on the metabolic rate and the resultant metabolic heat is the most significant source of heat in the exercising horse. Environmental factors such as solar radiation, ambient temperature and humidity and wind speed also play a role in the total heat gain of the horse.

Evaporation of sweat and water from the respiratory tract are the most important heat loss mechanisms in the exercising horse [141]. The rate of evaporation is almost totally dependent on ambient conditions. Other less significant mechanisms of heat loss include radiation to the environment, convection and conduction. All these factors are time and species dependent.

Several mathematical models have been formulated to describe whole body heat balance in homeotherms. According to the first law of thermodynamics, the total heat gain of the body can be expressed as:

$$\dot{H}_{total} = \dot{H}_{metab} + \dot{H}_{solar} - \dot{H}_{rad} \pm \dot{H}_{conv} \pm \dot{H}_{cond} - \dot{H}_{resp} - \dot{H}_{sweat}$$

This equation includes all the internal and environmental factors that have an influence on thermoregulation of the body. These factors include the heat generation due to basal metabolism and muscle activity ($\dot{H}_{metab}$), heat gain due to solar radiation ($\dot{H}_{solar}$) and heat exchange by means of radiation ($\dot{H}_{rad}$), convection ($\dot{H}_{conv}$), conduction ($\dot{H}_{cond}$), evaporation from the airways ($\dot{H}_{resp}$), and evaporation of sweat from the animal's skin surface ($\dot{H}_{sweat}$). This total heat balance model can be applied to any animal subject by alteration of a few of the parameters.

The structure and extent of the hair coat is primarily responsible for differences between thermoregulation in humans and animals. It is therefore necessary to consider coat structure and colour for application of models to animals. Several authors have described the influence of the coat structure and colour on the solar radiation, conduction and convection components of the heat balance equation. [38,39,97,199,200].

Heat loss through evaporation of sweat remains the most poorly defined parameter in the complete heat balance model. Evaporative heat loss has previously been estimated on the basis of sweat losses, and while it is understood that the environmental conditions significantly affect evaporation of sweat, these have not been quantified. This avenue of heat loss is the most significant parameter in terms of heat dissipation in the working horse [141]. It is therefore essential to quantify heat loss via this route. In the model described, we have assumed the skin surface of a sweating horse is adequately described as a body of water with a given surface area. We have described the interaction of the body of water with the prevailing environmental conditions.

When an animal expends energy, approximately 80% of that energy (in excess of 1.4 MJ per minute during maximal effort in a typical Thoroughbred horse) is released as heat [73]. This results in an increase in the animal's body temperature at a rate proportional to its work intensity. Horses are capable of high intensity work for prolonged periods and this has been exploited in various forms of competition. The horse has been expected to perform in climes vastly different from its northern cooler origins. Although there has been a degree of adaptation to warmer climes, the modern competitive equine athlete is often vulnerable to thermal distress [141]. The model described enables prediction of changes in the core temperature of horses working at a specific intensity under specific environmental conditions. This information may also be of use to predict the limits of work intensity and duration that an exercising horse can endure without experiencing thermal distress.

METHODOLOGY

If the core body temperature of most mammals rises uncontrollably from its normal resting value of ≈37°C clinical signs of, and even life-threatening, hyperthermia may become apparent [141]. During exercise, metabolic heat load increases in proportion with metabolic consumption of oxygen. Environmental conditions influence the degree to which this heat accumulates in the animal's body. Many mammalian species do, however, have some anatomical adaptations to maintain the brain temperature within closer tolerance of its normal body temperature [176].

Heat storage, or heat accumulation, can be defined as the imbalance resulting from an excess of heat gain over heat loss. It is the difference between the sum of the heat gains from all sources and the sum of heat sinks via all loss avenues. Heat storage, which is dependent on the heat dissipation, results in an increase in the animal's core temperature. The resultant increase is dependent on the body's specific heat capacity and its size, as described in equation (2). The model therefore predicts the rate of change of core temperature ($\Delta\dot{T}$).

$$\Delta\dot{T} = \frac{\text{Heat Storage (J/ min)}}{\text{Specific Heat capacity of the horse (J/ kg/°C)} \cdot \text{Body Weight (kg)}} \quad (\text{°C/ min}) \quad (2)$$

Although the rate of increase of the core temperature is mirrored by the rate of increase of the horse's deep rectal temperature, the changes in rectal temperature lag behind core temperature [92]. This should be considered when changes in rectal temperature are used as an indication of heat storage under field conditions.

Heat Gain

Metabolic heat gain ($\dot{H}_{metab.}$) and heat gain due to solar radiation ($\dot{H}_{solar}$) are the two most significant sources of heat. As the horse's work rate increases, the metabolic heat gain becomes more significant.

Metabolic heat

The metabolic heat production of the animal ($\dot{H}_{metab}$) can be estimated from the rate of metabolic oxygen consumption ($\dot{V}O_2$). The value of $\dot{H}_{metab}$ is dependent on the animal's work intensity and duration. During work, the metabolic rate increases due to increased muscular activity. Horses are capable of high metabolic rates, consuming in excess of 150 mℓ O_2/kg/min. It has been assumed that 80% of the calorific value of oxygen consumed doing work is released as heat, rather than mechanical work, and that each mℓ of O_2

consumed has an energy equivalent of 21 J [92]. The metabolic heat, $\dot{H}_{metab}$ can be calculated from equation (3).

$$\dot{H}_{metab} = 21 \cdot 0.8 \cdot \dot{V}O_2 \cdot BW \quad \text{(J/min)} \tag{3}$$

where, 21 is the energy equivalent of O_2 in J/mℓ, 0.8 is the fraction of the calorific value of oxygen released as heat, $\dot{V}O_2$ is the oxygen consumption in mℓ/kg/min and BW is the body mass in kilograms.

Solar Heat

Heat gain due to solar radiation ($\dot{H}_{solar}$) depends mainly on the animal's coat structure and colour. The darker the coat, the higher the radiant heat gain [199]. It has also been shown that with an increase in wind speed, the radiant heat gain of a dark coat decreases more rapidly than that of lighter coats [199]. There are no known reports of the relation between solar radiant heat gain and the coats of horses. Research done on pigeons [200] and other animals [38,39] have shown that $\dot{H}_{solar}$ can be calculated from equation (4):

$$\dot{H}_{solar} = A_\tau \left[a_L \cdot L_i + S_i \left[a_s + \left(\frac{\left(\frac{\rho c_p}{h}\right) - r_e}{r_e} \right) \cdot \left(\frac{1}{pt}\right) \cdot (2 - a_s) \right] \right] \cdot 60 \quad \text{(J/ min)} \tag{4}$$

where, A_τ is the exposed surface area of the animal (this area is assumed to be 85% of total surface area of the animal [59]), a_L the long-wave absorptivity for the animal, L_i the average long wave irradiance of the sun, S_i the average short wave irradiance of the sun, a_s the short-wave absorptivity for the animal, ρc_p the volumetric specific heat capacity of air, h the coat thermal conductance, r_e the external resistance to convective and radiative heat transfer and pt the probability that a penetrating ray will strike a coat element with thickness t.

The coat thermal conductance of the flank and belly of the horse have been reported by Tregear [191]. This study used coats removed from the torsos of freshly killed horses. Wind was blown over the coat in the same direction as occurs in the naturally running horse. The thermal conductance through the coat was found to be highly dependent on the hair density and on the speed of the air passing over the animal's surface. For the present study it was assumed that 70% of a horse's body surface is covered with the same hair density as the flank, while 30% of the body is covered with belly type coat. A value for the thermal conductance of the horse coat was calculated using this 70% -30% relationship between the data obtained by Tregear for the belly and the flank at different wind speeds .

The external resistance of the animal coat (r_e) can be calculated using equation (5).

$$\frac{1}{r_e} = \frac{4\varepsilon\sigma T_{air}^3}{\rho c_p} + \frac{1}{\xi\left(\frac{D}{u}\right)^{\frac{1}{2}}} \quad (5)$$

where, ε is the emissivity of the coat (assumed to be equal to 1 [150]), σ is the Stefan Boltzman constant, T_{air} is the ambient temperature, ρc_p the volumetric specific heat capacity of air and ξ the convection constant for a specific air flow. Assuming laminar flow across the body of the horse, the value of ξ can be taken as $307S^{½}/m$ [199,200]. D is the characteristic diameter measured across the trunk of the animal, and u the travelling speed of the horse (or the net sum of travel and wind speeds). Mitchell *et al.* [150] showed in humans that the emissivity is independent of skin colour. They obtained a value for emissivity of 0.997 for all skin colours. In most studies on animals, an emissivity of 1.0 was assumed for the coat [38,39]. Therefore, the horse coat emissivity was taken as 1.0 for the purposes of this study.

The actual values for the absorptivities a_L and a_S of the horse coat are unknown. Hutchinson and Brown performed a study on samples of cattle coats of differing colour and structure [97]. The absorptivity of the coats was measured using spectrophotometric techniques. This study showed that radiation absorptivity of cattle coats varies with different coat colours. In the present study, it was assumed that horses have a similar coat structure to cattle. From data described previously by Hutchinson and Brown [97], the wavelength dependence of absorptivity can be divided into two ranges: a short wave range from 0.3 μm to about 1.3 μm and a long wave range from 1.3 μm to 2 μm. In these two ranges a mean value for white, black and brown coat colours can be estimated individually. Hutchinson and Brown [97] showed that for short wave radiation, the mean absorptivity for the different coat colours were: a_s(white) = 0.68, a_s(brown) = 0.72 and a_s(black) = 0.8. They also showed that for long wave radiation, the mean absorptivity for all three colours was a_L=0.6.

The probability that a penetrating ray will strike a coat element with thickness t, namely pt, is dependent on the time of day. In previous studies, only one value of pt was assumed for the specific kind of skin surface used in each particular study [39,199]. According to Cena and Monteith [39], a general value for pt for a specific coat can be calculated from equation (6):

$$pt = nd \cdot \tan\left[\arccos(t/\ell_s)\right] \tag{6}$$

Where, n is the number of hairs per m^2 of coat, d the mean diameter of the individual hair, t the coat thickness, and ℓ_s the mean length of the hair. For the purposes of this study, the long wave irradiance (L_i) was taken as 0.94 kW/m^2 and the short wave irradiance (S_i) as 0.18 kW/m^2, which are typical of a clear summer's day in Pretoria, South Africa.

Heat Losses

Respiratory heat loss

Hodgson *et al.* [92] concluded in their study conducted on horses that heat loss from the pulmonary circulation ($\dot{H}_{resp}$) increases as exercise progresses. Furthermore, this progressive increase in heat loss may be related to increase in alveolar ventilation that occurs with increasing exercise duration in horses. Recent studies on human subjects [88] showed that increased respiratory heat loss can be affected by increased minute volume ($\dot{V}$). This is directly related to evaporative and convective heat loss from the respiratory tract. Both these variables are dependent on an increase in the core temperature of the subject. Evaporative heat loss is a major component of the respiratory heat loss and increases with increasing $\dot{V}$ [88]. The role of respiratory heat loss in maintaining thermal balance varies from species to species, and has been shown to be the primary route for heat dissipation in some species.

The total respiratory heat loss can be calculated from the sum of the convective and evaporative components as shown in equation (7):

$$\dot{H}_{resp} = \dot{V}_E \cdot \rho c_P \cdot (T_e - T_i) + La \cdot (W_e - W_i) \quad \text{(J/min)} \qquad (7)$$

Where, $\dot{V}_E$ is the minute volume, ρc_P the volumetric specific heat capacity of air, T_e and T_i the temperatures of the expired and inspired air, respectively, La is the latent heat of vaporisation of water, and W_e - W_i is the difference between expired and inspired water vapour [88]. In exercising horses one can assume that the inspired air temperature is the same as the ambient temperature. Hodgson *et al.* [92] estimated an expired air temperature of 34°C in exercising horses. This value was used in the predictions made in the present study. It should be noted that the specific heat capacity of air is not constant and is dependent on its density, temperature and water vapour content.

Convective heat exchange from the lungs is dependent on the pulmonary ventilation and the difference between the temperature of the expired air and ambient air temperature and humidity. Pulmonary ventilation is related to metabolic rate and this effect is accounted for by the first term of equation (7). The equation for respiratory heat loss derived by Mitchell *et al.* [151] cannot be used on horses because respiratory heat loss in horses is likely to be more significant than in humans. Calculating respiratory heat loss from metabolic heat production alone is therefore not accurate and the evaporative water loss from the respiratory system must be included in the calculation.

Evans *et al.* [57] concluded that the minute volume ($\dot{V}_E$) is linearly related to sub-maximal exercise intensity. They derived an equation for the relationship between the minute volume and oxygen consumption; equation (8):

$$\dot{V}_E = 214.804 + 7.39\,\dot{V}O_2 \quad (\ell / \min) \tag{8}$$

Where, $\dot{V}O_2$ is in mℓ/kg/min.

Evaporation heat loss due to sweating

The importance of evaporative heat loss ($\dot{H}_{sweat}$) in the horse is well recognised. Exercise intolerance demonstrated by anhidrotic horses highlights the role that sweat evaporation plays in maintaining thermal balance of exercising horses [137]. Horses with compromised sweating capabilities overheat easily, often with severe clinical implications [137].

In most previous studies, heat loss due to sweating is estimated from the change in body mass during the period of work. This probably overestimates effective evaporative heat loss as excess sweat is often lost as it drips from the horse. If one assumes that the skin surface of a sweating horse is adequately represented by a body of water and that there is a convectively stable atmosphere then the equation (9) describing the molecular diffusion of water vapour into free atmosphere [94] can be used to estimate heat loss due to sweating.

$$\dot{H}_{sweat} = \frac{La \cdot [3.2127 + 1.922\,u] \cdot (P_s - P_a)^{0.88} \cdot \rho_{sweat} \cdot A}{1440} \quad \text{(J/ min)} \qquad (9)$$

Where, La is the latent heat of vaporisation of sweat, u the air speed over the horse, p_s the saturated water vapour pressure of air at ambient temperature, p_a the actual water vapour pressure of air (p_s·[humidity of air]), ρ_{sweat} the density of sweat, and A the surface area of the horse. Due to the lack of data describing the thermodynamic properties of equine sweat, it is assumed that sweat has thermodynamic properties similar to water. Further research is required to determine how the latent heat of evaporation and vapour pressure of horse sweat varies with changes in composition. For this study, the relation of surface area of the horse to body weight described by Hodgson *et al.* [92] was used. The skin surface area (A) is related to body weight by equation (10):

$$A = 1.09 + 0.008 \cdot BW \qquad (m^2) \tag{10}$$

Where, BW is the body weight of the horse in kg.

Radiative heat loss

Any heated body can radiate heat to the environment. Heat loss due to radiation ($\dot{H}_{rad}$) is dependant on the surface area of the horse. The most important variable in this equation is the surface temperature. This surface temperature is dependent on the metabolic heat of the animal and the ambient conditions, which include ambient temperature and humidity, and cloud conditions. In the horse, heat loss due to radiation ($\dot{H}_{rad}$) can be calculated from equation (11) [59]:

$$\dot{H}_{rad} = 60(A_\tau \ \varepsilon \ \sigma \ T_s^4) \qquad (J/\min) \tag{11}$$

where, A_τ is the area emitting long wave radiation, ε is the emissivity of coat, σ the Stefan Boltzman constant, and T_s is the coat surface temperature.

Convective heat transfer

When there is air movement around a body, convection ($\dot{H}_{conv}$) occurs. Free convection occurs in still air decreasing the boundary-layer resistance as the temperature difference increases between the coat surface and the air [138]. Forced convection occurs when the body is exposed to moving air. Heat gain or loss due to forced convection can be calculated using equation (12). In this equation, the heat transfer rate is related to the total temperature difference between the surface of the horse and the air, and the surface area [94].

$$\dot{H} = 2\, h_c A\, (T_s - T_{air}) \cdot 60 \qquad (J / min) \tag{12}$$

Where, A is the surface area, T_s is the coat surface temperature, T_{air} the air temperature and h_c is the heat transfer coefficient at film temperature which can be calculated from equation (13):

$$h_c = Nu \cdot \frac{k_a}{x} \tag{13}$$

where, Nu is the Nusselt number, k_a is the thermal conductivity of air at film temperature, and x the length of the horse measured from the point of the shoulder to the tuber sacrale. The film temperature is the mean of the animal's surface temperature and the air temperature. Assuming the horse has a constant temperature over its entire body surface, the Nusselt number can be calculated from equation (14):

$$Nu = 0.332\ Rey^{1/2}\ Pr^{1/3} \tag{14}$$

where, Rey is the Reynolds number and Pr is the Prandl number. The

Reynolds number, which includes air speed and certain characteristics of the airflow across the animal's body, can be calculated using equation (15):

$$Rey = \frac{\rho_f ux}{\mu_f} \tag{15}$$

Where, ρ_f the density of air at film temperature, u the air speed over the horse, x the length of the horse and μ_f the dynamic viscosity of air at the film temperature [138].

The Prandl number relates the relative thicknesses of the hydrodynamic and thermal boundary layers and can be calculated from equation (16):

$$Pr = \frac{c_{pf}\ \mu_f}{k_a} \tag{16}$$

Where, c_{pf} is the specific heat capacity of air at the film temperature, μ_f the dynamic viscosity of air at film temperature, and k_a is the thermal conductivity of air at film temperature. These parameters were obtained from heat transfer tables for particular ambient conditions [94].

The Nusselt number describes the air layer and laminar airflow over the body. The effect of turbulence generated by the hairy coat of the horse is unknown and as in previous studies [138] was ignored.

Conductive heat transfer

Heat transfer due to conduction ($\dot{H}_{cond}$) plays a minor role in the heat balance of the horse. Conduction can cause either heat gain or heat loss, depending on the temperature differences between the animal and the environment [40]. The effect of this mechanism of heat exchange is not significant when compared to other factors described, and can probably be ignored [138]. The conductive heat loss factor may play a more significant role in the total heat balance when the different thicknesses and structures of summer and winter coats are considered. The conductive heat transfer is given by:

$$\dot{H}_{cond} = -\frac{k_c A}{t}(T_s - T_{skin}) \cdot 60 \quad (J/min) \tag{17}$$

Where k_c is the thermal conductivity of the animal coat, A the surface area, t the thickness of the coat, T_s the coat surface temperature and T_{skin} the skin temperature. A value of 0.036 W/m/°C for k_c of felt and hair was given by Holman [94] and was used for predictions made in this study. No values for the surface temperature of the horses during exercise were available. In a study done by Naylor *et al.* [157], subcutaneous temperatures of the neck and back of the horse were measured during low-intensity exercise (40% of $\dot{V}O_2max$, speed range 3.6 - 4.1 m/s) on a treadmill in a temperature-controlled laboratory (21-22°C). These temperatures were assumed to be similar to skin temperatures, and thus were used in verifying the model in the present study.

In South Africa the thickness of the sweat saturated coat of Thoroughbred horses is approximately 1 mm during summer and 3 mm during winter. The difference between skin and surface temperatures is so small for coats of this thickness that the heat loss due to conduction is negligible.

In all the models used in this study where air speed was a variable, it was assumed that air speed was equivalent to the actual travel speed of the horse and that the direction was opposite to the direction of travel of the horse. When applying these equations to field conditions the wind and travel components can be summed using component vectors in the travel direction.

Comparison of model with experimental data

The predictions generated by the described integrative model were compared to data reported by a number of workers. The variables describing the typical Thoroughbred horse are presented in Table A-1 and were the basis of the calculations.

Comparison with treadmill laboratory data:

The conditions within treadmill laboratories are generally controlled and therefore easily determined. Much data has been published describing heat balance of horses working in such laboratories [92,157]. Under these conditions solar radiation can be eliminated from the model. The thermodynamic characteristics were obtained from various thermodynamic steam tables [195,201]. The ambient temperature was 22 °C and the relative humidity was 40%. Changes in skin temperature were obtained from data published by Naylor *et al.* [157] for similar ambient conditions. Since the effect of work intensity on skin temperature kinetics has not been reported, the same skin temperature profile was used at all work intensities. Initial predictions were made at 10-minute increments. The skin temperatures used in this study were 35.8, 37.5, 39.2, 39.6, 39.7 °C at 0, 10, 20, 30, and 40 minutes of exercise, respectively [157]. The coat thermal conductivity was taken from data published by Tregear [191]. The difference between expired and inspired water vapour for the analysis was taken as 33.39 g/min [127].

Effect of solar radiation:

The effect of solar radiation on the heat balance of the animal as determined by lab the model was studied by adding the solar radiation components to the laboratory conditions presented above.

Table A-1: Characteristics of a typical Thoroughbred horse

Parameter	**Value**
Body Weight, BW	474 kg
Characteristic diameter, D	1.6 m
Length of horse, x	1.8 m
Coat Thickness, t	0.001 m
Length of hair, ℓ_s	0.03 m
Mean diameter of hair, d	0.0001 m
Number of hair/m^2, n	12 x 10^6
Thermal conductivity of coat, k_c	0.036 W/m/°C
Long wave absorptivity, a_L	0.6
Specific heat capacity of air, c_p	3 470 J/g/°C
Emissivity of coat, ε	1
Latent heat of H_2O vaporisation	2 428 kJ/ℓ
Stefan Boltzman constant, σ	5.67x10^{-8} W/m^2/°C^4
Convection constant of airflow, ξ	307 S^{½}/m
Short wave absorptivity, a_s	0.72

Table A-2: Summary of data defining the three work intensities used in the validation of the model

Work intensity		Speed (m/s) at 10% slope	Coat thermal conductance, h ($W/m^2/^oC$)
% of max.	$\dot{V}O_2$ (mℓ/kg bwt/min)		
40	50	4	11.51
65	86	6.8	14.45
90	117	8.5	15.59

Table A-3: Comparative summary of the time duration calculated for the horse to reach a critical temperature of 42 C and that reported by Hodgson *et al.* (1993) for different exercise intensities

Running speed (m/s) at 10% slope	% of $\dot{V}O_2$max	Time to reach critical temperature	
		Predicted	Experimental data
4	40	30	N/C
6.8	65	13.5	17.7
8.5	90	8.8	7.5

N/C, the time to reach the critical temperature was not reported in this study for this specific exercise intensity. From extrapolation of the plots presented in this study the time was estimated to be greater than 38 min.

Table A-4: Comparison of the respiratory heat loss predicted by by the model with the heat loss from the lungs reported by Hodgson *et al.* (1993) for a laboratory temperature of 22°C and a humidity of 40% for 3 different exercise intensities.

Running speed(m/s) at 10% slope	% of $\dot{V}O_2max$	Respiratory heat loss ($\dot{H}_{resp}$) (kJ/min)		
		Predicted	Experimental data	
4	40	89.539	60.5 after 3 min	198.5 after 38 min
6.8	65	93.394	151.2 after 3 min	259.5 after 15 min
8.5	90	96.179	166.3 after 3 min	408.2 after 9 min

RESULTS

Comparisons were made between published data [92,105] and predicted data at 40, 65 and 90% of $\dot{V}O_2$ max. Further details of the exercise conditions are summarised in Table A-2. The air speed generated by fans in the laboratory, and not the running speed of the horse, was taken as the air speed over the horse. Results predicted by the model and the carotid artery blood temperature data presented by Hodgson *et al.* [92] are compared in Figure A-1. The predicted and measured times for the horse's core temperature to reach a temperature of 42°C (nominated as the critical core temperature for the purposes of this study) are presented in Table A-3. The respiratory heat loss predicted by the model is compared with the experimental data reported by Hodgson *et al.* [92] in Table A-4. Figure A-2 shows a comparison between the rate of change of core temperature predicted by the model, that of the pulmonary artery reported by Jones and Carlson [105], and that of the carotid artery reported by Hodgson *et al.* [92].

The relationship between the predicted rate of change in core temperature and ambient humidity is presented in Figure A-3. These data were calculated at a work intensity eliciting 90% of $\dot{V}O_2max$ and ambient temperatures of 22°C and 30°C, other variables were taken from Table A-1. The effects of humidity and air speed over the horse on $\dot{H}_{sweat}$ are presented in Figure A-4.

The effect of solar radiation on the rate of change in core temperature ($\Delta\dot{T}$) at various humidities is presented in Figure A-5. Figure A-6 presents $\Delta\dot{T}$ for the absorptivities corresponding to different coat colours. The relationship between the solar heat gain and the coat absorptivity is presented in Figure A-7

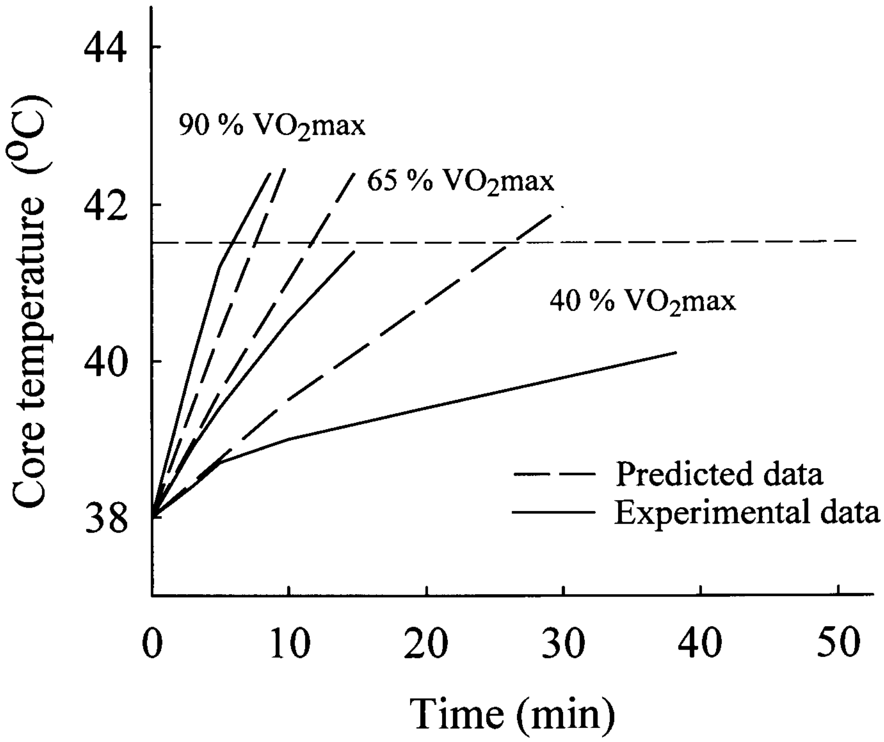

Figure A-1 : Plot of predicted core temperature and carotid artery temperature reported by Hodgson *et al.* (1993) at three different work intensities in Thoroughbred horses. The predicted values were calculated for a temperature of 22°C and a relative humidity of 40% to simulate the laboratory conditions under which the experiments were done.

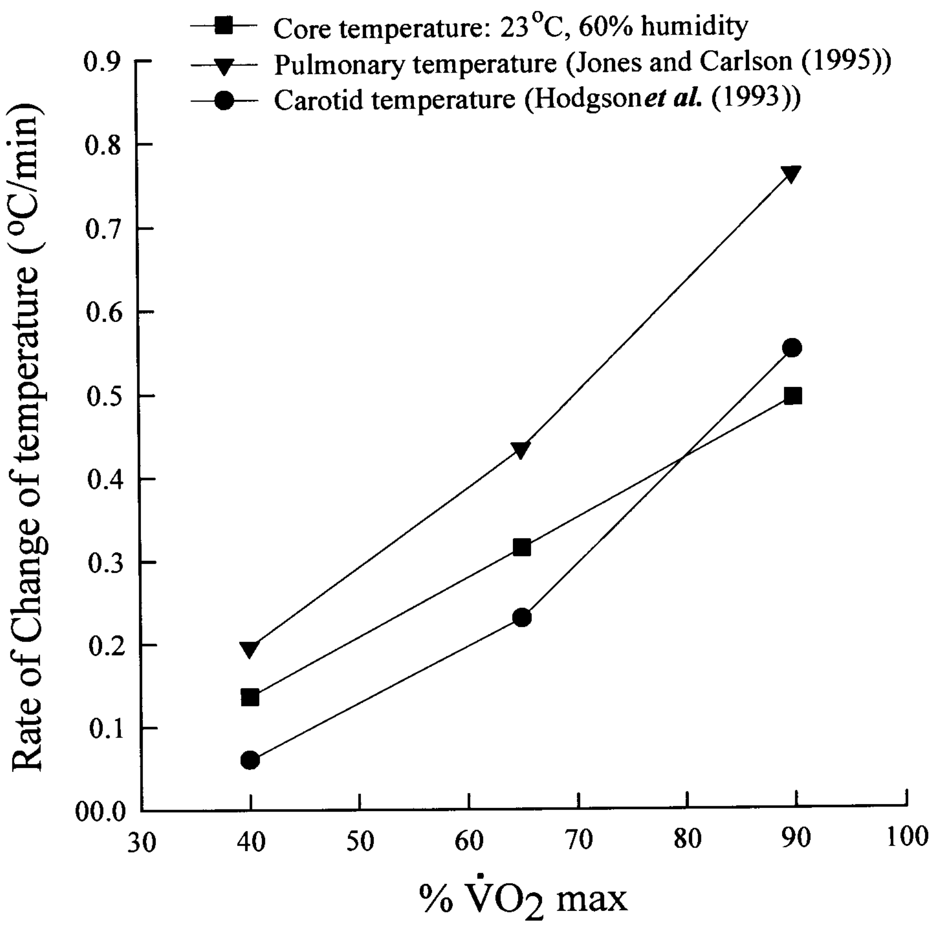

Figure A-2 : Comparison between the rate of change in core temperature as predicted by the model ($\Delta\dot{T}$), the rate of change in pulmonary artery temperature reported by Jones and Carlson (1995), and the rate of change in carotid artery temperature reported by Hodgson *et al.* (1993) at three different work intensities in horses.

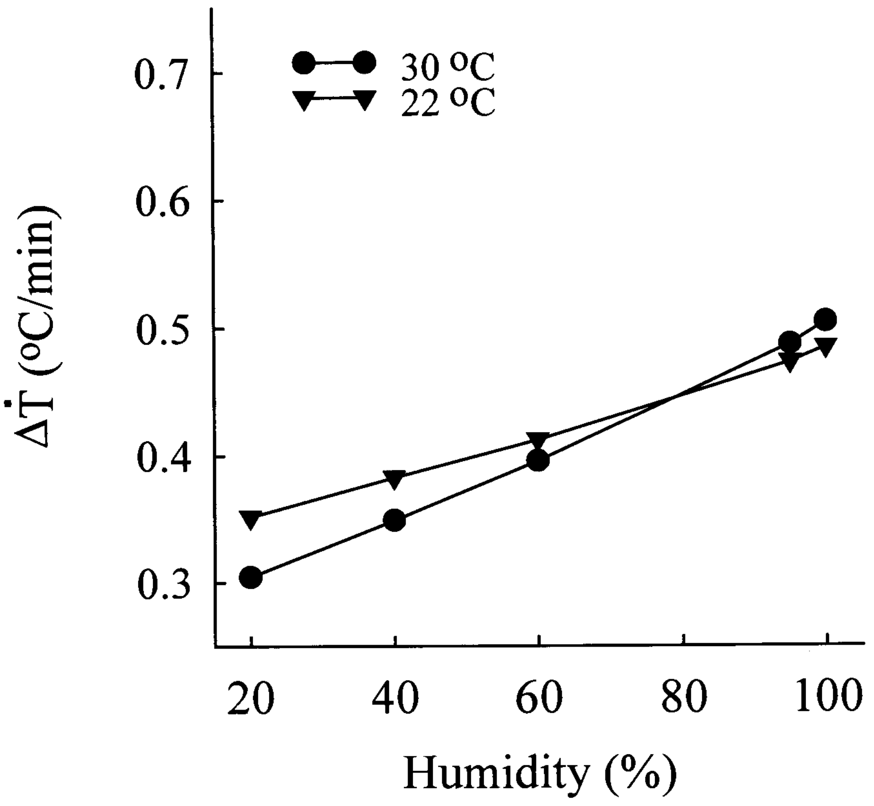

Figure A-3: The predicted effect of increasing humidity on the rate of change of core temperature of an average Thoroughbred horse exercising at 90% of $\dot{V}O_2max$ in ambient temperatures of 22 and 30°C.

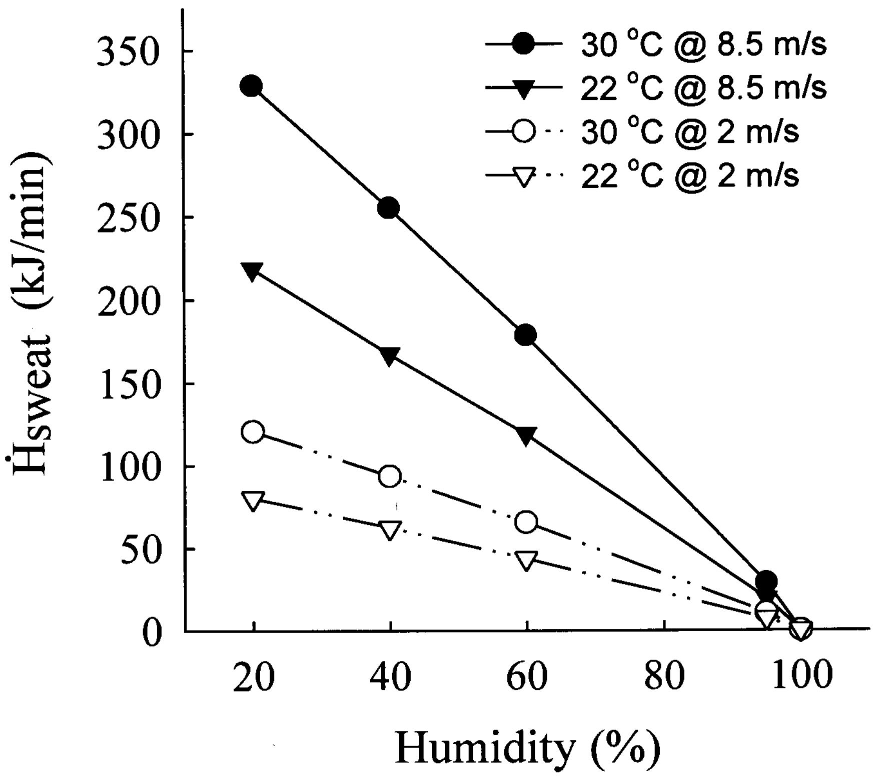

Figure A-4 : Plots summing the predicted effects of varying humidities at two temperatures and two air speeds on heat loss by evaporation of sweat for a typical Thoroughbred horse exercising at 90% of $\dot{V}O_2max$.

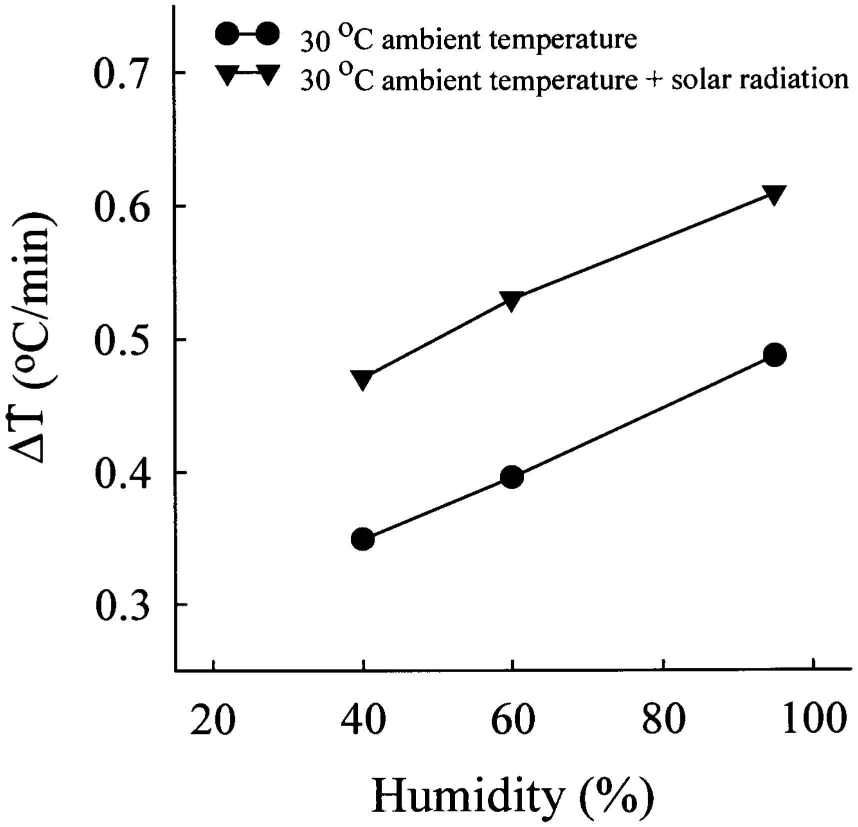

Figure A-5: The predicted effect of solar radiation on the rate of change of core temperature ($\Delta\dot{T}$) at different humidities for a typical Thoroughbred horse exercising at 90% of $\dot{V}O_2max$..

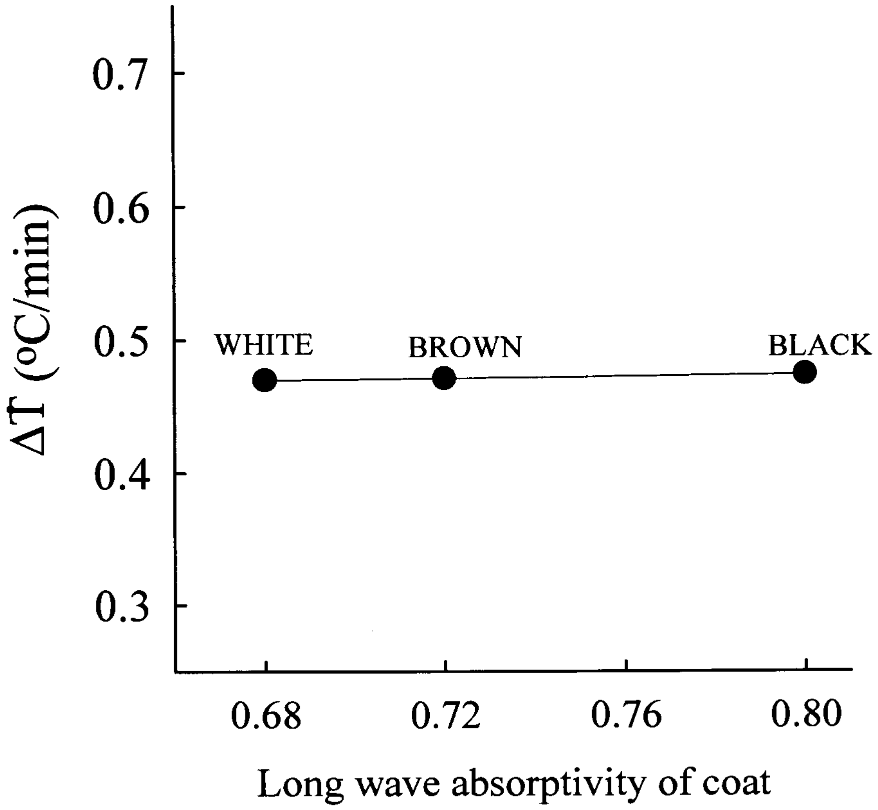

Figure A-6: The predicted effect of long wave absorptivity due to different coat colours on the rate of change of core temperature ($\Delta\dot{T}$) for a typical Thoroughbred horse exercising at 90% of $\dot{V}O_2max$ at a temperature of 22°C, relative humidity of 40%, long wave irradiance of 0.94 kW/m^2 and short wave irradiance of 0.18kW/m^2

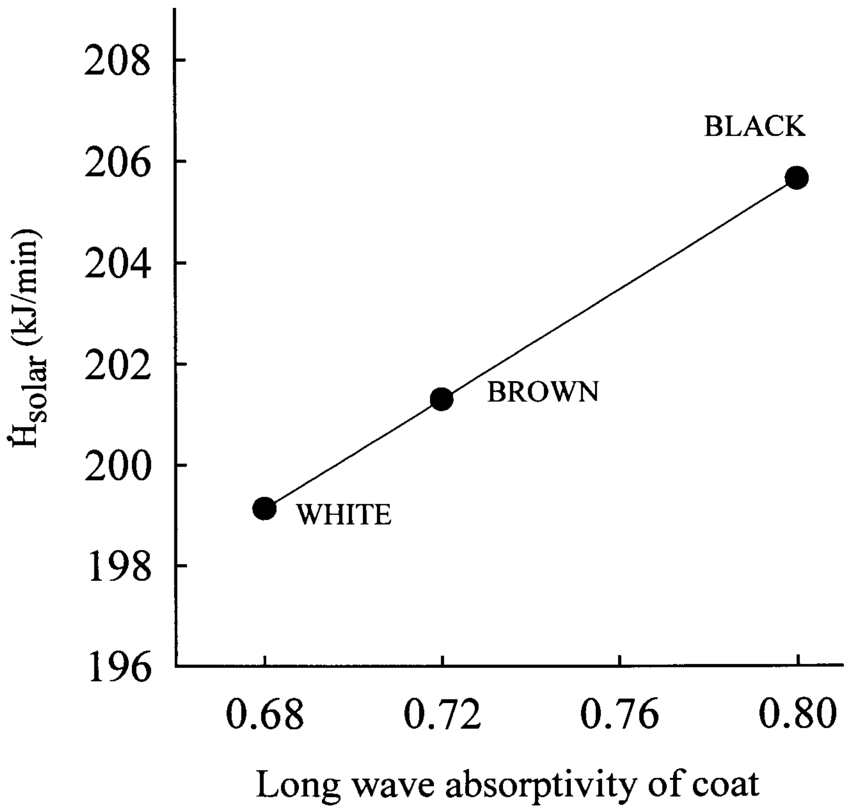

Figure A-7: The predicted effect of different long wave absorptivities due to different coat colours on solar heat gain ($\dot{H}_{solar}$) for a typical Thoroughbred horse assuming a long wave irradiance of 0.94 kW/m^2 and a short wave irradiance of 0.18kW/m^2.

DISCUSSION

It is apparent that as the work duration increases, the disparity between the predicted core temperature and the measured temperature increases. This is most easily illustrated during low intensity exercise where the exercise duration exceeds 30 minutes, however, at higher intensities, the respective data are also divergent as exercise progresses. At 90% of $\dot{V}O_2max$, the model initially underestimates the core temperature. As exercise progresses, the predicted data approaches the experimental data and if exercise progressed beyond 9 minutes, the model would probably overestimate the core temperature. At the two lower work intensities, the predicted data and the experimental data are very similar for the first 5 minutes. Estimations of core temperature beyond 5 minutes increasingly exceed the experimental data as exercise progresses.

Respiratory heat loss has been reported to increase as exercise progresses at all intensities [88,92]. However, the mechanism by which this occurs has not yet been explained nor modelled. The model presented therefore does not describe a similar trend. If these trends (presented in Table A-4) were superimposed on the data described by the model, the deviations of the model data from the experimental data at all work intensities would be smaller.

The balance of the heat was assumed to be lost via sweat evaporation, radiation and convection, of which evaporation of sweat was most significant. We assumed that the horse had a layer of sweat over its entire body 5 minutes after commencing exercise. The evaporative heat loss is dependant on the environmental conditions and assuming the temperature, humidity and air speed were constant, the model predicted the evaporative heat loss under the laboratory conditions to be similar at all work intensities. Lund *et al.* [127] showed that respiratory heat dissipation can compensate when evaporative heat dissipation reaches its maximum rate for the given conditions. Air speed over the entire surface of the horse is important for maintenance of core temperature. When exercising on a track, increases in speed result in greater air movement over the body, allowing more heat to be lost via the evaporation of sweat. In contrast if the speed of air movement over the body is lower than the running speed, which may occur when a horse exercises on a treadmill, inadequate evaporative heat loss is likely to occur, thereby dramatically increasing the risk of thermal stress if exercise is continued.

In our model, heat loss via convection accounted for about 5% of the total heat load during the first 10 min. Heat loss via radiation was the least significant, accounting for less than 1% of the total load. Although heat loss due to convection and radiation increased with increasing skin temperature and time, their contribution to overall heat balance was small.

The comparison presented in Figure A-2 shows that the rates of change of core temperature predicted by the model are closer to the results reported by Hodgson *et al.* [92] than to those calculated using the equations reported by Jones and Carlson [105]. The exercise test used by Jones and Carlson was conducted on the flat while that of Hodgson *et al.* was performed at a treadmill inclination of 10 %. Jones and Carlson did not report maximal oxygen uptake of their experimental subjects and did not relate any of their data to maximal oxygen uptake. These differences in experimental design makes direct comparison of the results difficult. The large fluctuation in laboratory temperature and humidity reported by Jones and Carlson further complicates these comparisons. These limitations highlight the need to perform comparative studies using similar experimental protocols and under controlled conditions.

<u>Effects of increasing humidity:</u>

Figure A-3 clearly shows that humidity has a major effect on thermal balance of the exercising horse. The air temperature determines the quantity of water vapour that the air can hold. The environmental ambient temperature and humidity are therefore interdependent in determining the evaporative heat loss of the exercising horse, which led us to conclude that the heat loss by sweating is independent of sweat rate. The elevated core temperature experienced during hot, humid conditions is a consequence of decreased evaporative heat loss ($\dot{H}_{sweat}$). The evaporative heat loss decreases with increasing humidity. Figure A-4 shows that as relative humidity tends toward 100%, the air becomes totally saturated with water vapour and evaporative heat loss tends toward zero. Heat can then only be lost via the respiratory system, convection, radiation and conduction. The respiratory heat loss will, however, be compromised as it depends, to an extent, on evaporation from the airways. The effect of air speed over the horse on evaporative heat loss at different humidities is also shown. These results show the importance of creating sufficient air movement over the horse when it is exercising at different exercise intensities on a treadmill. Failure to do so may result in unnecessary exposure of the horse to conditions that could result in heat stress.

Research by Hodgson *et al.* [92] has shown that the sweat rate of horses is closely related to the temperature of the blood in the carotid and pulmonary arteries. Kerr and Snow [111] investigated the sweat rate of horses during endurance exercise and concluded that the sweat rate gradually increased during the first 2 to 3 kilometres and was then maintained at a constant rate throughout the ride.

It could be proposed that evaporation from a saturated hair coat is not as effective as from the skin surface. Hodgson *et al.* [92] have shown that evaporation from the skin cools the subcutaneous blood flows, a hair coat saturated with sweat could behave as an insulating layer between the evaporative surface and the skin. The clipping of the hair coat of cattle has been shown to aid evaporative heat loss [1].

Figure A-5 shows solar radiation does affect the rate of increase of the core temperature of the horse. Cloud cover and the altitude determine the intensity of solar radiation. There is evidence that cities with high temperatures combined with high humidity (e.g. Hong Kong and Durban, South Africa) generally experience high cloud cover under such conditions. This therefore reduces the overall heat gain when evaporative heat loss is compromised. The absorptivity of the coat, which is determined by the colour of the hair, is often considered to significantly affect the heat gain [97]. Figure A-6 shows that coat colour does not significantly affect the rate of change of the core temperature. The component of heat gain as a result of the coat colour, shown in Figure A-7, compares well with results presented by Finch *et al.* [59] for white and black goats.

CONCLUSION

The deviations of the predictions of our model from the published experimental data [92,105,157] may be partially explained by incomplete data describing the environmental conditions under which the reported trials were carried out. However, the comparisons indicate that aspects of the model do not completely describe the behaviour of the mechanisms involved in dissipating metabolic heat. The predicted respiratory heat dissipation is lower than the experimental data and does not describe a similar ramping trend as exercise duration progresses. This ultimately results in an overestimation of the rate of change in core temperature during exercise. The model describing evaporative heat loss was derived experimentally from evaporation from a water pan, and the air flow over such a pan and the horse may be significantly different. The thermodynamic characteristics of horse sweat are unknown. Previous studies have assumed water and sweat have similar thermodynamic characteristics. It has been shown, however, that horse sweat contains protein, the concentration of which is higher at the onset of sweating [52] and has high salt concentrations [111]. The protein in horse sweat is known to reduce surface tension, enabling the sweat to wet the hair coat rather than forming droplets that can run off. Salts added to liquids are known to reduce vapour pressure [201]. Reducing vapour pressure reduces evaporation rate, and may also effect the latent heat of vaporisation. The effect of protein and salt on these characteristics of horse sweat warrants further investigation.

The reasonable correlation between the predictions of the integrated mathematical model presented and data of other researchers shows that the thermal balance of working horses can be modelled. However, the model, as it is presented here, requires refining before it can be applied with confidence to predict the thermal status of the equine athlete.

The study has shown which of the parameters in the model have the greatest influence on the heat balance of the exercising horse. It has also illustrated shortcomings in the current model. It has shown that the respiratory heat loss model is inadequate and warrants further experimental work in order to establish the mechanisms behind the reported increase in respiratory heat loss with exercise duration. Evaporative heat loss via sweating has been modelled with a reasonable degree of confidence, it should, however, be refined with experimental verification. Ultimately, the model should reasonably predict the intensity and duration of work a horse should be able to maintain under specific environmental conditions before experiencing thermal distress.

APPENDIX B

THERMOREGULATION - BASE MECHANISMS AND HYPERTHERMIA

Thermoregulation is the most important regulation system in homeothermic animals. [73] Such animals must maintain their body temperature within a very narrow range (37 - 40°C) despite extreme variations in metabolic rate and environmental conditions. [141] Physical work has the greatest effect on the metabolic rate and the resultant metabolic heat is the most significant source of heat in exercising horses. Environmental factors such as solar radiation, ambient temperature, humidity and wind speed also play a role in heat balance of the horse. Evaporation of sweat and water from the respiratory tract are the most important heat loss mechanisms in the exercising horse and the rate of evaporation is almost totally dependent on ambient conditions. [141]

When an animal expends energy, approximately 80% of that energy (in excess of 1.4 MJ/min during maximal effort in a 500 kg horse) is released as heat. [73] This results in an increase in the animal's body temperature at a rate proportional to its work intensity. Horses are capable of high intensity work for prolonged periods and this has been exploited in various forms of competition. Horses are also often expected to perform in climates substantially different from those to which they are acclimatized. Although there has been a degree of adaptation to warmer climes, the modern equine athlete is often vulnerable to hyperthermia and heat stress. This is further exacerbated by the fact that elite equine athletes are often required to travel to distant locations where the environment may be significantly different from that to which they are acclimatized. The staging of major international competitions under particularly stressful environmental conditions has highlighted awareness of heat balance of equine athletes recently. This has prompted research in the field and therefore an increase in the depth of knowledge of this aspect of equine athletics.

HEAT BALANCE

In homeotherms, energy balance is related to the maintenance of body temperature within a narrow range and is dependent on the dissipation and retention of metabolic heat. There is thus an environmental temperature range, which is (1) species, (2) breed, (3) climate, and (4) 'clothing or coat' dependent within which the animal can reduce it's energy consumption and still maintain energy balance. This temperature zone, termed the thermoneutral zone, is the temperature range where the basal metabolic rate is lowest. The basal metabolic rate of a sedentary animal is often referred to as the cost of living. [197]

Conversion of chemical energy to mechanical energy is extremely inefficient with approximately 80% of the total chemical energy used during muscular contraction released as heat rather than physical work. [26] The balance between heat gain and heat loss is continually disturbed, either by changes in metabolic rate (exercise being the most powerful influence) or by changes in the external environment. Heat is produced by virtually all chemical reactions occurring in the body, and thus metabolism sets the basal level of heat production, which can be increased by skeletal muscular contraction or the action of several hormones. [197] Heat gain due to solar radiation can also be significant but as a horse's work rate increases, the metabolic heat gain becomes more significant.

HEAT GAIN

The breakdown of organic molecules liberates energy from intramolecular bonds. This energy is utilized by cells in their performance of various forms of biological work (muscle contraction, active transport, synthesis of molecules). The first law of thermodynamics states that energy can neither be made nor destroyed but can be converted from one form to another. Thus, internal energy liberated during breakdown of organic molecules can either appear as heat or be used to perform work. The body is incapable of converting heat into work, but heat is vital for maintaining body temperature.

Biological work can be divided into two categories: (1) external work, i.e., movement of external objects by contracting skeletal muscles; and (2) internal work, which includes all other forms of biological work. All internal work is ultimately transformed into heat except during periods of growth. One of several examples of this is the internal work that is performed during cardiac contraction that ultimately appears as heat generated by the resistance to flow through the blood vessels. Thus, the total energy liberated when cells catabolize organic nutrients may be transformed into body heat, appear as external work, or be stored in the body in the form of organic molecules (fat or glycogen). The total energy expenditure of the body is therefore summarized by the equation:

Total energy = internal heat produced + external work performed + energy stored

Many factors influence the body's metabolic rate. In the measurement of basal metabolic rate (BMR), standardized test conditions must be maintained. The subject must not have eaten for 12 hours, must be in a state of physical and mental rest and be at a comfortable temperature. These conditions are termed basal, but the BMR is not the minimum metabolic rate. The subject's metabolic rate may be lower during sleep. BMR, as defined, is extremely difficult to achieve and measure in animals. Metabolic rate can be elevated by a number of factors including, body temperature and environmental temperature. Any form of stress, including illness, can also raise metabolic rate. [197] The ingestion of food causes an increase in metabolic rate of between 10 and 20%. It has been shown that this increase is not only due the digestion of the food but also the processing of the nutrients by the liver. Measurement of BMR in ungulates is not practical since it is difficult to attain a postabsorptive state and complete rest. The rate of O_2 consumption (Vo_2) under thermoneutral ambient temperature of a resting animal is commonly accepted as a convenient baseline for measuring various energy increments, such as heat increments of muscular work, feeding and thermoregulation. Some factors affecting "resting" heat production (HP) in ungulates include body size, species, breed and feed intake.

The relationship between mammalian body weight and resting HP has been extensively studied by Brody [26] and Kleiber. [116] Their studies revealed that resting HP is proportional to the animal's body mass to the power of 0.75 (i.e. a 100% increase in body weight is equivalent to a 75% increase in metabolic rate). Based on this finding, they proposed the term "physiological weight" or "metabolic body size" (i.e., body weight^{0,75}). They also showed that while this relationship is constant for adults of many species, it may not hold true for growing animals. [26] While this relationship is generally true, it has been shown that the resting HP per unit metabolic weight of cattle is higher than that of sheep. [75] Furthermore, Zebu cattle have a lower resting HP than the European and Afrikander breeds. [198,212] Although no studies have reported similar differences in horses, one could expect that lighter breeds may have a significantly lower resting HP than the heavier breeds that originate from northern Europe.

Under thermoneutral conditions, HP also depends on the quality and quantity of feed intake. [76] In horses, it has been shown that the replacement of dietary hay with grains reduces HP, [116] which can be further reduced by dietary fat supplementation. [63] Fasting also decreases HP but its effect is dependent on previous nutritional level. [74] Restriction of water intake and dehydration also decrease HP of many animals exposed to hot or cold environments [54,206,215]. The calorigenic hormones, (epinephrine, thyroid hormone (TH), growth hormone (GH), and glucocorticoids) all influence the metabolic rate of mammals. An increase in the plasma concentration of epinephrine may increase heat production by 30 %. Thyroid hormone (TH) also increases the oxygen consumption and heat production of most body tissues. [20,135] Administration of GH to cattle acclimated to a thermoneutral and a hot temperature increases HP by 30 to 60%. [218] Injection of hydrocortisone has also been shown to increase HP of cattle acclimated to thermoneutral and hot environments. [220]

The resting oxygen consumption of adult horses is between 2.2 and 4.2 ml/kg/min. [189] During maximal exercise the oxygen consumption may increase 40 to 60-fold to between 140 and 187 ml/kg/min. [50] Metabolic heat production of horses exercising at this intensity can exceed 1.4 MJ/min and would result in an increase in body temperature of approximately 1°C per minute if no heat was dissipated. The metabolic heat load of an endurance horse exercising at a mean speed of 8 m/s is approximately 0.6 MJ/min and would result in an increase in body temperature of approximately 21°C per hour if no heat was dissipated. Thoroughbred horses race over distances that require maximal effort for between 1 and 3 minutes and if the total heat load generated during such exercise were to accumulate it would result in an increase in temperature of approximately 4°C. Horses can tolerate acute changes in body temperature of this magnitude [66,92] provided the stored heat can be dissipated following cessation of exercise. The magnitude of the heat that accumulates during endurance exercise in horses can only be tolerated if adequate heat loss occurs throughout the event.

HEAT TRANSFER

Heat is transferred to or from a body by means of thermal gradients. There are four prime mechanisms whereby heat exchange can occur: radiation, convection, conduction and evaporation. Homeothermy requires a balance between heat produced by an animal, or gained from the environment, and that dissipated to the environment. Conductive, convective and radiative heat loss are of minor importance while evaporation of sweat and water from the respiratory tract are vital heat loss mechanisms in the exercising horse. [141]

Conduction refers to the direct transfer of heat between surfaces that are in contact and results in either heat gain or heat loss, depending on the temperature differences between the animal and the environment. [40] In exercising horses, most of this transfer is to air which has a very low thermal conductivity and thus conductive heat loss plays an insignificant role when compared to other mechanisms and can therefore be ignored. [138] Conductive heat loss is directly proportional to skin temperature and is inversely proportional to coat thickness. The limbs, head and neck of animals have a very high surface area to mass ratio and thus the majority of conductive heat loss occurs from these parts of the body. Shunting of blood away from the skin of the extremities limits conductive heat loss in animals exposed to low environmental temperatures while local vasodilation enhances heat loss from the extremities in animals exposed to high temperatures. [162] The increased thickness of winter coats reduces conductive heat loss and plays an important role in reducing heat loss from horses exposed to low environmental temperatures.

Convection occurs when there is heat transfer between two media at different temperatures. Free convection occurs in still air decreasing the boundary-layer resistance as the temperature difference increases between the coat surface and air. [138] Forced convection occurs when the body is exposed to moving air, as occurs during exercise [149]. Heat loss due to convection depends on the temperature difference between the surface of the horse and the air, surface area of the horse and the air speed over the horse. Free convection at the skin can contribute significantly to heat loss when ambient air temperatures are low. Convective heat exchange also occurs in the respiratory system and is dependent on pulmonary ventilation and the temperature difference between inspired and expired air.

Radiative heat transfer occurs when electromagnetic radiation is absorbed or emitted at the body surface. Any object exposed to sunlight absorbs solar, or short wave, radiation. Long-wave radiation is absorbed or emitted from the skin surface whenever there is a temperature difference between the animal and its environment. Heat loss due to radiation is primarily dependent on the skin surface temperature of the horse, but is also influenced by the skin surface area of the horse. The metabolic heat of the animal and ambient conditions, which include ambient temperature and humidity, and cloud conditions, determine surface temperature. The heat load from solar radiation can exceed 15% of the maximal metabolic heat production when animals are exposed to bright sunlight. [166]

In exercising horses, evaporation of sweat is the most important mechanism whereby heat is lost. [141,153] Evaporation of 1 liter of water can dissipate 2.4 MJ of heat. This is equivalent to the heat produced in approximately 6 minutes of endurance exercise or 2 minutes of high intensity exercise. The rate of evaporation is dependent on the water vapor pressure gradient between the body surface and the environment and on the rate of air movement over the body surface. During exercise in environments with a low humidity, evaporation is very efficient and can account for up to 65% of total heat loss. [153] When the humidity is very high the vapor pressure gradient between the body surface and the environment is smaller and less evaporation occurs. Under such conditions, sweat production usually exceeds the rate at which sweat can evaporate and sweat drips from the skin, thus loosing the benefit of evaporative heat loss.

Significant evaporative heat loss also occurs when inspired air is almost fully saturated with water at a temperature similar to core temperature as it passes over the moist surfaces of the upper respiratory tract. Heat lost via this mechanism is dependent on ambient humidity and minute ventilation. It has been estimated that between 15 and 25% of total heat loss can occur via respiratory heat loss. [90] It has also been shown that increased respiratory heat loss can be used as a compensatory mechanism when evaporative heat dissipation from sweating reaches its maximum rate for the ambient environmental conditions. [127,145]

THERMOREGULATION

Thermoregulatory mechanisms maintain the homeotherm's core body temperature within a narrow range by regulating heat accumulation and heat dissipation. In exercising horses, metabolic heat is produced in the working muscles and is lost from the body surface. These mechanisms are therefore responsible for distributing blood to the working muscles and subcutaneous vascular beds thus facilitating convective transfer of heat to the body surface. Peripheral thermoreceptors located in the skin, skeletal muscle, abdomen, spinal cord and hypothalamus detect changes in thermal load and produce a proportional output. The output of these peripheral temperature sensors is integrated in the hypothalamus and results in appropriate thermoregulatory effector activity [21]. In exercising horses, the primary thermoregulatory effectors are the circulatory system and the sweat glands.

Blood flow provides a very efficient means of transferring heat by convection and by altering blood flow to various organs, the circulatory system acts as a major thermoregulatory mechanism. The circulatory system plays its role as a thermoregulatory effector by increasing cardiac output and by redistribution of cardiac output, particularly blood flow to the skin. These adjustments in blood flow are so effective that thermal stability can be maintained under thermoneutral conditions by balancing peripheral vasodilation and vasoconstriction. Blood flow to the skin increases on exposure to heat resulting in conduction of heat to the body surface that increases skin temperature and convective heat loss from the body. As the heat load increases, increased blood flow to the skin also provides the latent heat for vaporization of sweat and supplies fluid for sweat production. When exposed to low environmental temperature, blood flow to the skin is reduced thus reducing skin temperature and limiting heat loss from the body.

Arteriovenous anastamoses (AVAs) connect arteries directly to veins in the skin thereby bypassing capillary beds. The opening of these vessels greatly increases blood flow through the skin thereby increasing heat loss. Skin blood flow is primarily controlled by the sympathetic nervous system. Response to heat results in vasodilation of arterioles and AVAs, while vasodilation of arterioles and veins occurs in response to cold. Heat exposure in horses results in an increase in blood flow to the skin, which is achieved by increasing cardiac output without a reduction in blood flow to other tissue vascular beds. [145]

During exercise, metabolic heat production is proportional to the intensity of exercise and heat is transferred from the working muscles to the body core, thus increasing core temperature. Sweating is initiated at a certain core temperature and continues at a rate proportional to the increase in core temperature. Under most environmental conditions, heat loss from the surface matches the rate of metabolic heat production and body temperature stabilizes at a temperature higher than resting core temperature. In horses, while sweating is under sympathetic nervous control there does not appear to be direct innervation of equine sweat glands. Sweating therefore occurs due to the humoral stimulation of β_2-adrenergic receptors on the sweat glands. During exercise, increased circulating epinephrine concentration is sufficient to cause sweating. [56]

HEAT BALANCE OF HORSES

Horses are capable of performing exercise at maximal metabolic rates that are twice those of elite human athletes and therefore the mass specific heat load of performance horses is double that of man. [91] Despite this, horses have a surface area to mass ratio that is approximately half that of man (Man - 1:35-40 and horse 1:90-100). Therefore, during maximal exercise, horses may be required to dissipate approximately 4 times more heat per unit of body surface area than man.

At the onset of exercise the accumulation of heat by the body is relatively rapid. As the various heat dissipation mechanisms are activated, the rate of heat accumulation decreases and the core body temperature reaches a plateau and remains relatively stable if heat production and heat dissipation are balanced. This increased core body temperature does have the advantage of improving muscle performance, facilitating the release of oxygen from the red blood cells and increasing maximum heart rate. The relatively slow rate of the increase of core body temperature is an indication of the body's capacity for heat storage. It has been shown that changes in deep rectal temperature lag significantly behind changes in core body temperature and that as the large hind gut of the horse has a high capacity to store heat, it probably plays an important role in heat storage during high intensity exercise of short duration. [92] The ability of the horse to compete successfully in short duration events when the conditions are thermally stressful is relatively good as a result of the body's capacity to store heat that is dissipated after the event. This allows the horse to perform at a high intensity for a short duration, without the danger of developing hyperthermia. The conditions experienced during high intensity exercise of short duration are probably similar to those that wild equids experience in 'fright or flight' thus allowing the animal to escape danger and restore heat balance once the danger has been averted.

A horse working at moderate intensity, with an oxygen consumption of 30 to 40 liters/min produces approximately 628 kJ of heat per minute. If this workload is maintained for an hour, the total metabolic heat production would be 37,6 MJ. In order to dissipate this amount of heat by evaporative processes alone would require the complete evaporation of approximately 15 litres of water. The rate of evaporation of this water depends on the environment's capacity to absorb the evaporated water vapor. The environment's capacity to absorb evaporated water vapor is dependent on the temperature and water vapor pressure (humidity) gradient between the skin surface and the environment and the air velocity over the skin surface. The combination of these factors has led to the development of the concept of 'effective temperature'. This concept has been extended by the use of the Wet Bulb Globe Temperature (WBGT) which includes total radiation and therefore provides an extremely useful index for quantifying environmental heat load. [177,178]

When the environmental heat load is high, evaporative heat loss may not be able to keep pace with the exercise-induced heat load and heat gain from the environment and may thus pose a serious risk to the equine athlete, particularly when performing protracted submaximal exercise. Under these conditions, the sweat rate often exceeds the rate at which sweat can evaporate. This results in sweat dripping from the horse and contributes to the large fluid losses which can occur under these conditions. [33] With continued exercise, where fluid losses are sufficiently large (<5% of bodyweight) heat dissipation by evaporative cooling from the skin is compromised either by decreased conduction of heat from the core or subsequent to reduction in cardiac output and sweat rate [91]. Under such conditions, the heat storage capacity of the body can easily be exceeded [105] and the horse's temperature may exceed the critical temperature resulting in hyperthermia.

HYPERTHERMIA

During moderate to high intensity exercise under experimental conditions, fatigue occurs in horses when central blood temperature approaches 42.5°C. [92,93] Since heat balance is under the control of the thermoregulatory center in the hypothalamus, critical upper temperature limits have been proposed for the central nervous system. [24] A recent study in horses [142] demonstrated that fatigue occurs when hypothalamic temperature approaches 41.5°C. This study also reported that hypothalamic temperature was consistently more than 1°C less than central blood temperature and therefore provides evidence to show that horses have a mechanism that allows selective cooling of the brain. During high intensity exercise in horses, muscle temperature increases rapidly and may reach 45°C. [106] Above this temperature, some enzymes have been shown to denature, thus altering metabolism, [24] and therefore 45°C probably represents the safe upper limit for muscle temperature.

CLINICAL SIGNS OF HYPERTHERMIA

Hyperthermia occurs most commonly in poorly conditioned horses that are required to exercise for prolonged periods under adverse ambient conditions (high temperature and humidity). Thermoregulatory failure in horses is commonly referred to as the "exhausted horse syndrome" [33,35]. Affected horses show fatigue, hyperthermia and profound fluid and electrolyte losses. Clinical signs include depression, weakness, reduced exercise capacity, increased heart and respiratory rate and elevated rectal temperature (often >42°C). Mucous membranes are often congested and capillary refill time is increased. Fluid and sodium loss associated with excessive sweating result in hypotonic dehydration [33] and affected horses often loose the desire to drink, due to insufficient osmotic stimulus. Sweating response is often reduced resulting in the skin being hot and dry. Serious metabolic disturbances including exertional rhabdomyolysis, synchronous diaphragmatic flutter, gastrointestinal stasis, colic and renal failure may also develop. Severe cases may progress to show ataxia, collapse and convulsions. Coma and death are rare consequences of extreme heat stress.

MANAGEMENT OF HYPERTHERMIC HORSES

Early recognition and medical intervention are critical in the management of patients suffering from heat exhaustion. Management includes immediate termination of exercise and application of simple cooling methods that take advantage of the immediate environment. All these strategies should be aimed at dramatically increasing radiant, convective and evaporative heat loss. The horse should be removed from direct sunlight if possible and placed in a shady area. Utilization of fans may be extremely beneficial to provide increased air movement over the horse's body surface. Repeated application of cool water to the horse's body also enhances heat dissipation. While this can be accomplished using sponges dipped in cold water, more aggressive cooling may be required if the horse is very hot. In such cases, water with a temperature of 2 to 8°C should be used and repeatedly applied using sponges, hoses or by pouring it directly on to the horse. Water applied in this fashion will become warm almost immediately and should thus be scraped off and fresh cool water applied. While the application of iced water was thought to result in reflex vasoconstriction of cutaneous vascular beds thereby reducing conduction of heat to the surface of the body, recent studies have shown that this aggressive approach to cooling is effective and is not associated with any adverse side-effects. [118,208] In these studies, rectal temperatures following use of iced water were significantly lower at all post exercise temperature measurements and the largest reduction in temperature occurred within 10 minutes of cessation of exercise. For this reason, this aggressive approach to cooling was widely employed by attending veterinarians and competitors during the 10 minute breaks in the endurance phase of the 3-day event competition of the Olympic games held in Atlanta during July 1996.

The horse's temperature should be monitored during the cooling process and the body temperature should be lowered as rapidly as possible to prevent damage to the central nervous system or other tissues. Cooling should start as soon as possible and should continue until body temperature is reduced to normal. Horses with severe heat stress are often dehydrated and usually require rehydration. As the dehydration is usually hypotonic, most of these cases will not drink voluntarily and it is therefore often necessary to administer sodium-containing fluids intravenously and/or orally if gut function is adequate. It is often necessary to administer 20 to 40 liters of fluid over a few hours. Isotonic solutions are recommended for intravenous administration. Normal saline (0.9% NaCl) supplemented with potassium chloride (approximately 20 mmol/l) is useful for replenishment of the most important ionic deficits. Administration of fluids by stomach tube is extremely useful when attempting to rehydrate horses, although care must be taken to ensure that ileus is not present. There are many commercially available oral replacement fluids that can be used. Some of these fluids contain glucose and glycine that enhance the uptake of fluids and electrolytes from the small intestine. As simple replacement fluid for oral administration can be made up by dissolving 20g of common salt (sodium chloride) and 20g of "Litesalt" (sodium and potassium chloride) in 5 liters of water. This results in an electrolyte composition of approximately 107, 28 and 132 mmol/l of sodium, potassium and chloride, respectively. [33] In horses with normal gut function, one can usually administer large volumes of fluid (up to 8 liters) and this can be repeated approximately every hour.

Synchronous diaphragmatic flutter (SDF) is seen most frequently in endurance horses performing in hot, humid climates. By itself, SDF is probably not dangerous but it is an index of significant electrolyte imbalances. [34] Such horses require prompt and vigorous fluid therapy to restore volume and correct electrolyte deficits. Horses with SDF generally respond well to the administration of intravenous solutions containing calcium. [34]

While heat stress is most common following prolonged exercise, hyperthermia can occur in horses in training for racing or performing high intensity exercise of short duration. This is most common in horses resident in areas with hot, humid tropical climates and is commonly associated with partial or complete anhidrosis.

Sweat production in response to an appropriate stimulus is decreased in anhydrotic horses, probably as a result of prolonged stimulation of sweat glands by circulating catecholamines. [14] Clinical signs of anhidrosis include the inability to sweat normally, diminished exercise tolerance and performance, tachypnea following exercise, and, in some cases, alopecia. At this stage, the only effective remedy is to move the horse to an area with a more temperate climate. The increased metabolic rate that results from increased circulating catecholamine concentrations observed in horses that become excessively excited, may predispose such animals to development of heat stress when they are exposed to adverse environmental conditions. The confinement of horses in poorly ventilated stables or transport vehicles in hot, humid environments can also induce heat stress. While horses that develop heat stress following high intensity exercise of short duration may occasionally collapse and even die, the clinical signs of heat stress of this type are generally mild when compared to those observed following endurance events. Clinical signs include unsteadiness, tachycardia, tachypnea, muscle cramping and a rectal temperature of up to 41°C. Dehydration is not common in these cases and application of iced water to the entire body surface following termination of exercise is usually sufficient to reduce the body temperature to normal.

PREVENTION OF HYPERTHERMIA

Recognition of the potentially harmful effects of high environmental heat load is vital to allow horses to train and compete safely under such conditions. The implementation of measures to minimize thermoregulatory demands and optimize fluid balance, helps reduce the impact of stressful environmental conditions. Such measures include estimation of the environmental heat load expected during the event, acclimatization of horses to the expected environmental conditions and dietary supplementation.

The Wet Bulb Globe Temperature (WBGT) Index [177] provides a means of quantifying the effective environmental heat load. In addition to the effects of ambient temperature and humidity, it also accounts for wind speed and radiative heat load. A retrospective study in which the WBGT Index was compared with the veterinary assessment of the degree of thermal stress experienced by the horses during a number of national and international competitions has clearly demonstrated the value of WBGT Index in quantifying local environmental thermal load. [178] In January 1996, the Fédération Equestre International (FEI) officially adopted the WGBT Index to ensure that local climatic conditions at the competitions site were accounted for in the design and management of competitions. Environments with a WGBT Index below 28 are suitable for the Speed and Endurance phase of 3-day-events, while environmental conditions giving a WBGT Index of above 33 may not be compatible with safe competition. When WBGT Index is between 28 and 33, it is essential that the competition proceeds with extreme caution and it may be necessary to modify the conditions of the competition. While these limits probably provide a realistic basis for planning of 3-day-event competitions further refinement of the WGBT Index is essential for its use to be expanded to other equestrian sports, e.g. endurance rides.

Regular exposure to high ambient heat loads result in a number of physiological adaptations that decrease the negative effect of environmental conditions on subsequent performance. This improved ability to thermoregulate is achieved by a combination of thermal and circulatory adaptations and is referred to as acclimatization. [125] In man, acclimatization is characterized by adaptations to circulatory and sweating responses which occur within 3 to 14 days of regular exposure to, and exercise under, thermally stressful conditions. These adaptations include; a reduced heart rate at the same exercise intensity, increased plasma volume, cardiac output, blood flow to the skin and sweating rate, onset of sweating at a lower core temperature which combine to result in a reduced core temperature at the same exercise intensity. [125] A recent study in horses has demonstrated that 3 weeks of daily exposure to, and exercise in, thermally stressful conditions results in a reduction in heart rate and core temperature at the same exercise intensity. [67] It is therefore advisable to ensure that the conditioning program of horses includes sufficient time, approximately 3 weeks, for acclimatization if horses are going to be expected to compete under hot, humid conditions. This acclimatization period is of particular importance for horses that are transported from cool to warm environments.

SUMMARY

Metabolic heat production is extremely high during exercise in horses. Thermoregulation in horses is primarily dependent on evaporative heat loss from sweating in particular. Under thermoneutral conditions these mechanisms are sufficient to allow horses to perform high intensity exercise for long periods. Under thermally stressful conditions, particularly high ambient humidity, the efficiency of evaporative heat loss mechanisms is compromised and may result in horses developing hyperthermia. Early recognition and vigorous treatment are essential to limit the consequences of heat stress in horses. Meticulous planning and management of equestrian events that are held under thermally stressful conditions are essential to ensure the welfare of competing horses and their riders. The conditioning program of horses expected to compete under thermally stressful conditions must also make adequate provision for acclimatization to the hot, humid conditions.