



UNIVERSITEIT VAN PRETORIA  
UNIVERSITY OF PRETORIA  
YUNIBESITHI YA PRETORIA

**CONTRIBUTION OF RESPIRATORY HEAT LOSS TO HEAT  
BALANCE IN THOROUGHBRED HORSES PERFORMING NEAR  
MAXIMAL EXERCISE UNDER THERMONEUTRAL AND HOT-  
HUMID CONDITIONS**

A THESIS

SUBMITTED TO THE  
FACULTY OF VETERINARY SCIENCE  
OF THE  
UNIVERSITY OF PRETORIA  
IN FULFILMENT OF THE REQUIREMENTS  
FOR THE DEGREE OF  
DOCTOR OF PHILOSOPHY

IN  
PHYSIOLOGY

BY

RAYMOND JOHN LUND

BACHELOR OF SCIENCE (ENGINEERING), UNIVERSITY OF CAPE TOWN, 1989

MASTER OF SCIENCE (PHYSIOLOGY) UNIVERSITY OF PRETORIA, 1996

JANUARY 2000

## **DEDICATION**

To all those who encouraged me to complete this thesis,  
Particularly my wife, Bernice,  
And parents, Howard and Jessie

## ACKNOWLEDGEMENTS

I wish to acknowledge and express my sincere appreciation to the following people:

**PROFESSOR ALAN GUTHRIE**, my promoter and director of the Equine Research Centre, for the insight, patience, guidance and wisdom. Thank you for the enthusiasm and for the friendship.

**PROFESSOR ROY MEINTJES**, my co-promoter from the Department of Veterinary Physiology, for his help and guidance.

**JANE NURTON**, colleague at the Equine Research Centre, for providing the positive stimulating help, motivation, enthusiasm and friendship.

**HENNING MOSTERT**, fellow student at the Equine Research Centre, for providing the positive stimulating and happy environment in which we work.

I am grateful to the following organisations whose generous financial assistance enabled the experimental work described in this thesis to be undertaken: The **TRANSVAAL/GAUTENG PROVINCIAL ADMINISTRATION**, the **HIGHVELD RACING AUTHORITY**, the **EQUINE RESEARCH CENTRE** and the **UNIVERSITY OF PRETORIA**.

The experiments described in this thesis would not have been possible without the excellent co-operation and patience of the subjects, the horses, who took part in the experiments.

## DECLARATION

I, *Raymond John Lund*, do hereby declare that the experiments presented in this thesis were conceived and executed by myself and, apart from the normal guidance from my supervisor, I have received no assistance.

Neither the substance nor any part of this thesis has been submitted in the past, or is being, or is to be submitted for a degree in the University or any other university.

This thesis is presented in fulfilment of the requirements for the degree of PhD.

Signed:.....



Date:.....

20 AUGUST 2000

## ABSTRACT

The purpose of the studies presented in this thesis was to develop a greater understanding of the contribution of respiratory heat loss to the thermal balance of exercising horses.

In the first experiment the effect of three different warm-up regimens on the thermal balance of Thoroughbred horses was investigated. The experiments showed that a low intensity warm-up was most beneficial aiding heat dissipation during subsequent exercise. The study also showed the heat loss by sweating is not restricted by the rate of sweat production, but by the evaporation rate of the sweat.

In the second experiment, horses were exercised to fatigue in thermoneutral and hot-humid environments. The evaporative heat dissipation from sweating and from the respiratory tract was severely impaired during the hot humid exercise protocol. There was a significant increase in the heart rate and the metabolic rate during the hot humid protocol, thus indicating the additional work done by the horse in an effort to dissipate the rapidly accumulating heat. The significantly shorter time to fatigue may be a mechanism to protect the horse from circulatory collapse as the circulatory demands for cardiac output exceed its capacity.

In the third experiment adaptations that the horse is able to make to alleviate the compromised evaporative heat loss were identified. These experiments showed that the horse is able to shorten its stride, increase minute ventilation and the velocity of the air in the conducting airways. The results presented also indicate that the horse is able to modify the evaporative area of the airways to enhance evaporative heat loss from the respiratory tract. The experiments also showed that during exercise in hot-humid environments, small changes in the evaporating surface vapour pressure have a significant effect on the vapour pressure gradient thus having a significant effect on the evaporating heat loss.

Finally, the lessons gained during the experiments presented in this thesis were used to revise and refine a mathematical model of the thermal balance of exercising horses. The resulting model is more accurate and easier to apply to use in the field.

## SAMEVATTING

Die doel van die studie was om 'n beter begrip te verkry van die bydrae van asemhalings-hitte-verlies tot die termiese balans van die volbloed renperd.

In die eerste eksperiment is die effek van drie verskillende opwarmings oefening roetines op die termiese balans van volbloed perde ondersoek. Die eksperimente het getoon dat 'n lae intensiteit opwarming die mees voordeligste is en hitte verspreiding gedurende die daaropvolgende oefening fase fasiliteer. Die studie het verder getoon dat hitte-verlies deur sweet nie beperk is deur die produksie van sweet nie, maar deur die tempo van die verdamping van sweet.

In die tweede eksperiment is die perde geoefen tot moegheid in 'n termoneutraal en 'n warm hoë humiditeit klimaat. Die verdampingshitte verbruik van sweet en van die asemhaling streek was baie benadeel gedurende die warm humiditeit oefening protokol. Daar was 'n merkende toename in die hartklop sowel as die metaboliese spoed tydens die warm hoë humiditeit omstandighede, wat daaropdui dat die perd addisionele werk moet doen in 'n poging om die vinnig opbouende hitte te verminder. Die heelwat korter tyd tot moegheid kan dalk 'n meganisme wees om die perd te beskerm teen

sirkulerende ineenstorting wanneer die sirkulêre vereistes van die vraag vir kardio uitset die kapasiteit daarvan oorsky.

In die derde eksperiment is die aanpassing wat deur die perd gemaak kan word, aangaande verdampingshitte-verlies geïdentifiseer. Hiedie eksperiment het getoon dat die perd oor die vermoë beskik om die spoed van lug in die lugweg te vertraag sowel as die spoed van die lug in die geleidingslugweg. Die resultate toon ook dat die perd oor die vermoë beskik om die asemhalingsarea te bevorder. Die eksperiment het ook getoon dat gedurende oefening in 'n warm humiede klimaat, minimale veranderinge in die verdampsarea 'n merkwaardige impak het op die verdampingshitte-verlies.

Ten slotte is die resultate van die studie gebruik om die wiskundige model van termiese balans van renperde aan te pas. Die aangepaste model is meer akuraat en is ook maklike om in die pratyk te gebruik.



## PUBLICATIONS EMANATING FROM THIS THESIS

1. Guthrie, A.J., Lund, R.J., (1997) Thermoregulation - Base Mechanisms and Hyperthermia. Veterinary Clinics of North America: K Hinchcliff – Extracted from the literature review presented in Chapters 2 and 3 :Appendix B.
2. Lund, R.J., Guthrie, A.J., Mostert, H.J., Travers, C.W., Nurton, J.P. and Adamson, D.J. (1996) Effect of three different warm-up regimens on heat balance and oxygen consumption of Thoroughbred horses. J. Appl. Physiol. 80: 2190-2197
3. Mostert, H.J., Lund, R.J., Guthrie, A.J., Cilliers, P.J. (1996) An Integrative Model for Predicting Thermal Balance in the Exercising Horses. Equine Veterinary Journal 22:7-15: Appendix A
4. Lund, R.J., Guthrie, A.J., Nurton, J.P., Mostert, H.J., Travers, C.W. and Hodgson, D.R. (XXXX) Respiratory Heat Loss from Horses in Extreme Hot-Humid and Thermoneutral Environments :Chapter 5
5. Lund, R.J., Guthrie, A.J. and Lyon, Q (XXXX) Design of a simplified Ultrasonic Air Flowmeter : Chapter 6
6. Lund, R.J., Guthrie, A.J., Nurton, J.P. and Meyer, C (XXXX) Respiratory Adjustments During Exercise in Hot-Humid Environments to Aid Heat Loss in Thoroughbred Horses: Chapter 7

7. Lund, R.J. and Guthrie, A.J. (XXXX) Refinements to a Mathematical Model of the Thermal Balance of Exercising Horses: Chapter 8

## TABLE OF CONTENTS

Dedication .....	ii
Acknowledgements .....	iii
Declaration .....	iv
Abstract .....	v
Samevatting .....	vii
Publications emanating from this Thesis .....	ix
Table of Contents .....	xi
List of Tables .....	xx
List of Figures .....	xxii
Chapter 1 .....	1—1
General Introduction .....	1—1
Chapter 2 .....	2—4
Review of Literature .....	2—4
Total Energy Balance, Metabolism and Heat Stress .....	2—4

1. Introduction .....	2—4
2. Total Body Energy Balance .....	2—9
Basic Concepts of Energy Expenditure and Caloric Balance .....	2—9
3. Heat Production.....	2—13
Mechanisms.....	2—13
Regulation of Heat Production .....	2—14
4. Thermoregulation.....	2—17
Observations in the Field.....	2—17
Control Mechanisms.....	2—20
Thermoregulation and work .....	2—20
5. Endocrinology and Heat.....	2—26
Thyroid Function.....	2—26
Adrenal Function .....	2—28
Pituitary Hormones.....	2—31
6. Thermal Environment .....	2—33
Abiotic Environmental Factors .....	2—33
7. The Animal and the Environment.....	2—36
Heat Exchange Between Animal and Environment.....	2—36
8. Heat Stress.....	2—42
Circulatory Changes In Heat-Stressed Animals.....	2—42
Effect of exercise in the Heat-stressed animal .....	2—45
Central Cardiovascular Changes .....	2—46
9. Effects on Respiration .....	2—48

Moisture Loss from the Respiratory Tract .....	2—48
Disturbance of respiration and blood gas concentrations.....	2—49
10. Thermal Stress and The Horse .....	2—53
Exercise Stress.....	2—53
Transport Stress.....	2—53
Thermal Stress.....	2—54
Medical Problems Associated with Heat Stress and Exercise ...	2—57
Management of Horses in Potentially Stressful Environments..	2—61
Calculation of metabolic heat production .....	2—64
Measurement of Heat Loss.....	2—65
12. Summary .....	2—67
Chapter 3 .....	3—69
Review of Physical Chemistry and Water Vapour Thermodynamics	3—69
1. Review of Thermodynamics, Gas Laws and Psychrometrics .....	3—69
Fundamental Parameters .....	3—69
Adiabatic Saturation .....	3—72
Calculation of Heat Transfer by Moist Gasses.....	3—75
Heat Transfer During Evaporation.....	3—77
Equine Sweat.....	3—81
Chapter 4 .....	4—89

The Effect of Three Different Warm-up Regimens on Heat Balance of Thoroughbred Horses.....	4—89
Abstract .....	4—89
Introduction.....	4—91
Materials and Methods.....	4—93
Experimental animals:.....	4—93
Experimental protocols.....	4—93
Determination of temperatures.....	4—94
Determination of metabolic response to exercise.....	4—96
Statistical analyses:.....	4—98
Results.....	4—99
Exercise time.....	4—99
Metabolic responses to the different warm-ups.....	4—99
Temperature responses to warm-up and exercise.....	4—100
Heat Production.....	4—103
Heat Storage.....	4—105
Heat Dissipation.....	4—105
Discussion.....	4—105
Acknowledgements.....	4—112
Chapter 5.....	5—113

Respiratory Heat Loss from Horses Performing Maximal Exercise in Hot - Humid and Thermoneutral Environments .....	5—113
Abstract .....	5—113
Introduction .....	5—115
Materials and methods .....	5—117
Experimental animals .....	5—117
Experimental protocols.....	5—117
Measurement of Oxygen consumption.....	5—119
Measurement of respiratory heat loss.....	5—119
Measurement of metabolic responses to exercise .....	5—119
Measurement of temperatures .....	5—120
Measurements of laboratory conditions .....	5—120
Statistical analyses.....	5—121
Results .....	5—123
Exercise time. ....	5—123
Metabolic responses to exercise .....	5—123
Temperature responses to warm-up and exercise.....	5—123
Heat Gain.....	5—124
Respiratory Heat Dissipation.....	5—124
Discussion .....	5—126
Acknowledgements .....	5—134
Chapter 6 .....	6—135

## Design and Construction of a Simplified Ultrasonic Air Flowmeter<sup>6</sup>—135

Abstract .....	6—135
Introduction .....	6—136
Principle of operation .....	6—139
Operation of the system .....	6—140
Construction of the Flowhead .....	6—143
Measuring Results and Discussion.....	6—149
Conclusions .....	6—152
Chapter 7 .....	7—153

## Respiratory Adjustments During Exercise in Hot-Humid Environments

### to Aid Heat Loss in Thoroughbred Horses ..... 7—153

Abstract .....	7—153
Introduction .....	7—155
Materials and Methods .....	7—157
Experimental animals .....	7—157
Experimental protocols.....	7—158
Measurement of Oxygen consumption.....	7—159
Measurement of respiratory heat loss.....	7—159
Measurements of temperatures.....	7—159
Measurements of laboratory conditions .....	7—160
Measurement of tidal volume and minute volume .....	7—160



Measurement of end expiratory gas temperature and respiratory frequency .....	7—161
Calculation of the changes of the evaporative area and the vapour pressure at the evaporating surface of the respiratory tract.....	7—162
Calculation of respiratory tract mean flow velocity and evaporative heat loss .....	7—163
Statistical analyses.....	7—163
Results .....	7—166
Oxygen consumption.....	7—166
Respiratory heat dissipation .....	7—166
Temperature responses to warm-up and exercise.....	7—166
Changes in respiratory dynamics .....	7—167
End Expired Gas Temperatures.....	7—168
Estimate of the relative change in the Evaporative Surface Area and Vapour pressure.....	7—169
Calculation of Respiratory Heat Loss .....	7—169
Discussion .....	7—179
Acknowledgements .....	7—191
Chapter 8 .....	8—191
Refinements to a Mathematical Model of the Thermal Balance of Exercising Horses.....	8—192
Abstract .....	8—192

Introduction .....	8—194
Model .....	8—197
Heat Losses.....	8—197
Comparison of model with experimental data .....	8—204
Results .....	8—205
Discussion .....	8—213
Conclusion.....	8—216
Chapter 9 .....	9—218
General Conclusions .....	9—218
Chapter 10 .....	10—220
References .....	10—220
Appendix A .....	A—257
<b>An Integrative Model for Predicting Thermal Balance in the Exercising Horses .....</b>	<b>A—257</b>
Abstract .....	A—257
List of Symbols and the Units of the Corresponding Variables.....	A—259
Introduction .....	A—261
Methodology .....	A—264
Heat Gain.....	A—265
Heat Losses.....	A—270

Comparison of model with experimental data .....	A—277
Results .....	A—281
Discussion .....	A—290
Effects of increasing humidity: .....	A—292
Conclusion.....	A—294
Appendix B.....	B—297
Thermoregulation - Base Mechanisms and Hyperthermia.....	B—297
Heat Balance .....	B—298
Heat Gain .....	B—299
Heat Transfer.....	B—303
Thermoregulation.....	B—306
Heat balance of horses .....	B—308
Hyperthermia.....	B—310
Clinical signs of hyperthermia .....	B—311
Management of hyperthermic horses .....	B—312
Prevention of hyperthermia.....	B—316
Summary .....	B—319

## LIST OF TABLES

Table 2-1: Summary of effector mechanisms in temperature regulation .....	2—6
Table 2-2 : Exhaustive Disease Syndrome .....	2—60
Table 4-1. Means and standard errors of various variables measured in 6 horses at rest, following warm-up, at fatigue and following 20 minutes recovery in response to 3 different warm-up regimens. ....	4—101
Table 5-1: Means and standard errors of variables measured in 5 horses at rest, prior to a warming up, following warming up, at the point of fatigue and 1 minute after fatigue whilst performing a standardised exercise to fatigue test under thermoneutral (TN) (20°C, 50% RH) and under hot humid conditions (HH) (35°C, 85% RH). * indicates means are significantly different at P<0.05. ....	5—122
Table 7-1: Means and standard errors of variables measured in 5 horses at rest, prior to a warming up, following warming up, after 5 minutes at 9.1 m/s and after 5 minutes recovery. Exercise was performed under hot dry (HD) (30°C, 35% RH) and under hot humid conditions (HH) (30°C, 85% RH). * indicates that means are significantly different at P<0.05. ....	7—165
Table 8-1: Characteristics of a typical Thoroughbred horse.....	8—205
Table A-1: Characteristics of a typical Thoroughbred horse.....	A—279
Table A-2: Summary of data defining the three work intensities used in the validation of the model .....	A—280

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 .....A—280

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. ....A—281

## LIST OF FIGURES

Figure 2-1: Body temperature as a balance of heat loss and heat gain .....	2—8
Figure 2-2: Streams of energy between the animal and environment .....	2—38
Figure 2-3: Conceptual model of environmental effects on the metabolism of animals .....	2—40
Figure 3-1: The Adiabatic Saturation process. Air enters the ‘saturator’ at point 1, moves over a pan of water and leaves at point 2 saturated with water vapour. There is no heat transfer during the process and the temperature of the mixture at point 2 is defined as the wet bulb temperature. ....	3—74
Figure 3-2: Sensible heating and cooling process described by a psychrometric chart .....	3—76
Figure 3-3: Schematic of a heating or cooling device .....	3—76
Figure 3-4: Boiling heat transfer coefficients for a heating surface in water at atmospheric pressure.....	3—78
Figure 4-1 Temperature in the pulmonary and carotid arteries and the rectum during no warm-up (X;A), race warm-up (R;B), and comprehensive warm-up (W;C) trials.....	4—102
Figure 4-2 Heat production (A) during different stages of the experiments and heat dissipation (B) via various avenues during the X, R and W trials.	4—104
Figure 5-1: Metabolic heat production and respiratory heat exchange during each phase of the standard exercise to fatigue tests under thermoneutral (TN) and hot-humid (HH) conditions. Respiratory heat exchange was	

significantly lower ( $P < 0.05$ ) during all phases of exercise in the hot-humid environment.....5—125

Figure 6-1 Block diagram of the ultrasonic air flowmeter system .....6—144

Figure 6-2 Relation of output voltage and air flow.....6—145

Figure 6-3 Respiratory gas flow trace from a horse galloping on a treadmill6—146

Figure 6-4 Cross section through the flowhead. Diameter of the respiratory tube is 110 mm.....6—147

Figure 6-5: Oscilloscope image of the output of 1. the signal received by the transducer; 2. the non-retriggerable monostable flipflop output preventing multi-triggering of the multivibrator; and 3. the burst triggering the multivibrator. ....6—148

Figure 7-1: Means and SE of oxygen consumption of five horses during warm-up, near maximal exercise and recovery under hot dry (HD) and hot humid (HH) conditions. ....7—170

Figure 7-2: Means and SE of respiratory heat loss of five horses during warm-up, near maximal exercise and recovery under hot dry (HD) and hot humid (HH) conditions. \* indicates values significantly different ( $P < 0.05$ )7—171

Figure 7-3: Means and SE of pulmonary artery temperature and rectal temperature of five horses during warm-up, near maximal exercise and recovery under hot dry (HD) and hot humid (HH) conditions. Long dash lines indicate lines used to determine the temperature lag between the pulmonary artery and the rectal temperatures.....7—172

- Figure 7-4: Means and SE of tidal volume (A), respiratory frequency (B) and minute volume (C) of five horses during warm-up, near maximal exercise and recovery under hot dry (HD) and hot humid (HH) conditions. \* indicates a significant difference ( $P < 0.05$ ). .....7—173
- Figure 7-5: Means and SE of the tracheal air velocity of five horses during warm-up, near-maximal exercise and recovery under hot dry (HD) and hot humid (HH) conditions. \* indicates values significantly different ( $P < 0.05$ ). .....7—174
- Figure 7-6: Means and SE of the temperature of the gas in the trachea measured at the end of the expiratory phase of the respiratory cycle in five horses during warm-up, near maximal exercise and recovery under hot dry (HD) and hot humid (HH) conditions. \* indicates values significantly different ( $P < 0.05$ ). .....7—175
- Figure 7-7: Vapour pressure of the respiratory tract evaporative surface calculated from the temperature of the saturated evaporative surface and the change in evaporative surface area relative to the area 1 minute after start of warm-up during exercise in hot-dry (HD) and hot-humid (HH) conditions. ....7—176
- Figure 7-8: Comparison of the percent reduction from the HD (30°C & 35% RH) to the HH condition (30°C & 85% RH) of the vapour pressure capacity of the environment and the respiratory heat loss with each phase of exercise. (Vapour Pressure Capacity =  $(p_{\text{Sat}} - p_{\text{Amb}})$ ) .....7—177



Figure 7-9: Comparison of measured respiratory heat loss from horses exercising during hot dry and hot humid conditions with the respiratory heat loss is calculated from tracheal air velocity and the relative surface areas of the evaporating surfaces. The calculated respiratory heat loss for the HH environment overestimated the heat loss when compared to the experimental data. This heat loss was corrected by applying a constant to the calculated data.....7—178

Figure 8-1: Graphic presentation of the relative proportions of the avenues of heat loss from horses during exercise. .... 8—207

Figure 8-2: Plot of predicted core temperature from the revised model, the Mostert model 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. ....8—208

Figure 8-3 : Comparison between the rate of change in core temperature as predicted by the Mostert model and the Revised model at the onset of exercise, 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. ....8—209

Figure 8-4: Comparison of the respiratory heat loss measured experimentally (Chapter 7) with the respiratory heat loss predicted by the model in hot-humid and hot dry conditions .....8—210

Figure 8-5: Plot of the heat loss by evaporation of sweat estimated using the Mostert model [153] and the Kerslake model [112]. Regression  $r^2 = 0.9999$  .....8—211

Figure 8-6 : Comparison of the pulmonary artery temperature presented in Chapter 7 and the core temperature predicted by the model during exercise in hot-humid and hot dry conditions.....8—212

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. ....A—283

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. ....A—284

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  $\dot{V} O_2\text{max}$  in ambient temperatures of 22 and 30°C.....A—285

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  $\dot{V} O_2\text{max}$ . .....A—286

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  $\dot{V} O_2\text{max}$ .....A—287

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  $\dot{V} O_2\text{max}$  at a temperature of 22°C, relative humidity of 40%, long wave irradiance of 0.94 kW/m<sup>2</sup> and short wave irradiance of 0.18kW/m<sup>2</sup> .....A—288

Figure A-7: The predicted effect of different long wave absorptivities due to different coat colours on solar heat gain ( $\dot{H}_{\text{solar}}$ ) for a typical Thoroughbred horse assuming a long wave irradiance of 0.94 kW/m<sup>2</sup> and a short wave irradiance of 0.18kW/m<sup>2</sup>.....A—289