

THERMOREGULATION IN BICYCLE ROAD RACING

by

Stephen Lyons Brown

B.Sc.(Kines), Simon Fraser University, 1978

THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE
in the Department
of
Kinesiology

© Stephen Lyons Brown 1984

SIMON FRASER UNIVERSITY

January, 1984

All rights reserved. This work may not be reproduced in whole or in part, by photocopy or other means, without permission of the author.

APPROVAL

Name: Stephen Lyons Brown
Degree: Master of Science (Kinesiology)
Title of Thesis: Thermoregulation in Bicycle Road Racing

Examining Committee:

Chairman: Dr. Thomas J. Smith

Dr. Eric Banister
Senior Supervisor

~~Dr.~~ John Dickinson

Dr. Robert Strath

Dr. Peter Hochachka
Department of Zoology
University of British Columbia
External Examiner

Date Approved: 19 January 1984

PARTIAL COPYRIGHT LICENSE

I hereby grant to Simon Fraser University the right to lend my thesis, project or extended essay (the title of which is shown below) to users of the Simon Fraser University Library, and to make partial or single copies only for such users or in response to a request from the library of any other university, or other educational institution, on its own behalf or for one of its users. I further agree that permission for multiple copying of this work for scholarly purposes may be granted by me or the Dean of Graduate Studies. It is understood that copying or publication of this work for financial gain shall not be allowed without my written permission.

Title of Thesis/Project/Extended Essay

Thermoregulation in Bicycle Road Racing

Author:

(signature)

Stephen L. Brown

(name)

January 23, 1984

(date)

ABSTRACT

Eleven trained male cyclists cycled 55 km without consuming food or beverage on the road and in the laboratory at a relatively constant velocity of 35.3 and 37.3 km·h⁻¹, respectively. Rectal temperature increased 1.5°C (p<0.05) and body weight decreased 2.0% (p<0.0005) following the road ride, but hematocrit changes were not significant. In the laboratory, each subject rode his own racing bicycle, converted to a stationary ergometer with a Racer Mate Wind Load Simulator. Road riding environmental conditions were simulated with fans (38.5 km·h⁻¹) and movie lamps (678 W·m⁻²). Each subject completed six trials at approximately one-week intervals, at 65% of his mean maximal oxygen uptake (4.97 litres·min⁻¹). Three trials were performed at 30°C, 50% RH — one each with wool, lycra, and cotton shorts and jersey. Rectal and skin temperatures, heart rate, hematocrit, body weight loss and thirst were not significantly different when wearing these different garments, but 83% more (p<0.01) sweat was retained in the wool clothes. Another three trials under the same basic conditions were performed at 20°C to 23°C to contrast thermoregulatory responses under typical laboratory conditions (no fans or lamps) with those under simulated outdoor conditions (fans and lamps, or fans only). Core temperature, hematocrit and thirst were not significantly different, but without the fans, 33% more (p<0.01)

weight was lost, skin temperature was 13% higher ($p < 0.0005$), 614% more ($p < 0.0005$) sweat was retained in the clothing and there was a trend ($p < 0.07$) for higher mean heart rate. Core temperature and heart rate rose exponentially following the onset of steady state work toward a steady state level but continued to rise ($p < .001$) throughout exercise. This progressive rise was more pronounced at 30°C than at 20°C and for moderately than for highly trained subjects. The results suggest that clothing is not a critical factor in thermoregulation during bicycle road racing under the conditions of this study. However, sweating rate may be substantial (1.0 to $1.3 \text{ l}\cdot\text{h}^{-1}$) and heat related disorders may occur during prolonged cycling without adequate rehydration. The wind encountered in actual road cycling apparently reduces thermoregulatory demands compared with stationary bicycle ergometry indoors. Failure to account for this enhanced cooling may result in overestimation of the physiological stress of actual road cycling.

QUOTATION

More people would recognize opportunity if it did not
so often come disguised as hard work.

Anonymous

ACKNOWLEDGMENTS

Many people shared their time and expertise in producing this thesis. I would like to thank Drs. Jim Morrison and Tom Smith for their helpful suggestions regarding experimental design, Rob Maskell for design and repair of hardware used in the experiments, George Wakeham for kindly loaning the industrial fans used to simulate outdoor environmental conditions, Chuck Wurster of Racer Mate, Inc. and Ian Johnson of Cicli Forza for providing some of the apparatus used in the experiments, Dr. Leigh Palmer for explaining how to calibrate heat flux transducers, and Vic Stobbs for operating the environmental chamber and working many overtime hours to accommodate a busy schedule of experiments. I appreciate the cooperation and patience of the subjects in the study: Andy Drinnan, Tom Gomez, Ian Johnson, Bruce Johnstone, John Lew, Bob McWhinnie, Kevin Pennock, Beau Pulfer, Mark Sims, Kory Sinclair, Bruce Spicer, Alex Stieda, Vic Therrien and John Winterdyke. I would also like to acknowledge the help of Gavril Morariu with photography, Lou Crockett with graphic art, Dianne Guenther, Pat Gillian, Nancy Stothers and Shannon Thomas with data entry, Drs. Nori Ison and Dave Goodman with statistical analyses, Dr. Samia Fadl with the heat balance calculations, and Margaret Sharon, Frances Atkinson and Wolfgang Richter with computer text formatting. My committee was especially helpful in designing and conducting the experiments and in writing and revising the thesis, and I would like to express my gratitude to Drs. John

Dickinson and Rob Strath for this help. Special thanks are due my senior supervisor, Dr. Eric Banister, for believing in me and for his academic guidance and financial support over the years. Finally, I would like to thank my partner, Teri Lydiard, for her support and understanding throughout this project.

TABLE OF CONTENTS

Approval	ii
Abstract	iii
Quotation	v
Acknowledgments	vi
List of Tables	xii
List of Figures	xiv
1.0. Introduction	1
1.1. Thermoregulation in exercise:	2
1.1.1. Core temperature:	2
1.1.2. Sweating:	5
1.1.3. Skin blood flow:	6
1.1.4. Dehydration:	7
1.1.5. Circulatory changes in prolonged exercise:	12
1.1.6. Bicycle ergometry in the laboratory compared with actual road cycling:	13
1.1.7. Limiting factors in prolonged submaximal exercise:	18
1.2. Traditional cycling clothing:	20
1.3. Purpose of the study:	23
2.0. Pilot studies:	26
2.1. Rationale:	26
2.2. Methods:	26
2.3. Results:	29
2.4. Discussion:	30
2.5. Conclusion:	31
3.0. Major study:	33

3.1. Experimental design:	33
3.2. Method:	34
3.2.1. Subjects:	34
3.2.2. Field study:	36
3.2.3. Laboratory study:	38
3.2.4. Maximal aerobic capacity:	47
3.2.5. Data entry and analysis:	48
4.0. Results:	54
4.1. Maximal oxygen uptake:	54
4.2. Field study:	55
4.2.1. Average cycling velocity:	55
4.2.2. Heart rate:	55
4.2.3. Thermoregulatory response:	56
4.3. Laboratory study:	58
4.3.1. Cycling velocity, oxygen uptake and ventilation:	58
4.3.2. Heart rate:	70
4.3.3. Time dependent changes in core temperature, heart rate, and oxygen uptake during prolonged steady-state bicycle exercise:	72
4.3.4. Differences in thermoregulatory responses to prolonged submaximal bicycling in the laboratory between highly trained and moderately trained cyclists:	74
4.3.5. Thermoregulation at 20°C ambient conditions with and without simulated radiant heat gain and wind velocity:	81
4.3.6. Thermoregulatory responses wearing different garments at 30°C:	85
4.3.7. Comparison of thermoregulatory responses in moderately and highly trained subjects during prolonged submaximal bicycling at 20°C and 30°C ambient temperature:	87

4.3.8. Hematocrit:	89
4.3.9. Thirst:	89
4.3.10. Heat flux:	91
4.4. Comparison of actual road cycling with simulated road riding in the lab:	91
5.0. Discussion:	94
5.1. Maximal oxygen uptake and heart rate:	94
5.2. Road ride:	94
5.3. Relative metabolic rate:	97
5.4. Oxygen cost of different cycling velocities:	98
5.5. Differences in thermoregulatory response to prolonged submaximal bicycling in the laboratory between highly trained and moderately trained cyclists:	101
5.6. Differences in thermoregulatory responses during laboratory ergometry compared with simulated road riding conditions:	107
5.7. Differences in thermoregulatory responses when exercising at 30°C in the laboratory wearing different garments:	112
5.8. Changes in oxygen uptake, core temperature, and heart rate during prolonged, steady-state exercise:	118
5.9. Comparison of thermoregulatory responses when cycling in the laboratory with simulated wind and radiant heat load at hot and moderate ambient temperature:	120
5.10. Hematocrit:	122
5.11. Heat flux:	124
5.12. Comparison of actual road cycling with simulated road riding in the laboratory:	126
6.0. Conclusions and directions for future research:	128
6.1. Experimental ergometer:	128
6.2. Relative metabolic rate during cycling:	129

6.3. Sweating rate:	129
6.4. Thermoregulatory responses during cycling when wearing different clothing:	130
6.5. Changes in heart rate, core temperature, and oxygen uptake during prolonged submaximal bicycling:	131
6.6. Laboratory ergometry compared to simulated road cycling:	132
References	133
Appendix 1	142
Appendix 2	143

LIST OF TABLES

TABLE		PAGE
1	Physical characteristics of subjects.	27
2	Maximal oxygen uptake and heart rate for subjects in the present study.	35
3	Physiological measures in a mixed group of elite and good male cyclists before and after a 55 km ride on the road.	57
4	The relationship between oxygen uptake and ventilation for highly and moderately trained cyclists during 55 km of laboratory cycling under various environment/clothing conditions.	69
5	Comparison of observed with predicted values of oxygen uptake on the Racer Mate Wind Load Simulator for a group of trained cyclists during 55 km of steady state submaximal cycling in the laboratory.	71
6	Progressive increases in core temperature and heart rate through three specified time intervals in a group of cyclists riding 55 km in the laboratory.	73
7	Time constants for the exponential increase in rectal temperature for moderately and highly trained cyclists under various environment/clothing conditions.	76
8	Time constants for the exponential increase in heart rate for moderately and highly trained cyclists under various environment/clothing conditions.	77
9	Significance of the difference between rectal temperature and heart rate responses for moderately and highly trained subjects for various environment/clothing conditions.	78

10	Thermoregulatory responses in a group of trained cyclists cycling 55 km in the laboratory at 20°C under standard laboratory conditions and under simulated road cycling conditions.	82
11	Heat stress indices in a group of trained cyclists according to the garments worn while cycling 55 km in the laboratory at 30°C under conditons of simulated wind and sun.	86
12	Pre-exercise hematocrit readings for a group of trained male cyclists measured on six separate occasions at approximately one week intervals.	90
13	Physiological and thermoregulatory responses in a group of cyclists during 55 km of cycling on the road at 15°C and in the laboratory at 20°C with simulated wind.	92
14	Values for maximal oxygen uptake of competitive male distance cyclists reported by other investigators.	95

LIST OF FIGURES

FIGURE		PAGE
1	The experimental ergometer used in the present laboratory study.	28
2	Time course of changes in heart rate and core temperature during 82 minutes of submaximal bicycling in the laboratory at 20°C for a group of highly trained cyclists.	60
3	Time course of changes in heart rate and core temperature during 82 minutes of submaximal bicycling in the laboratory at 30°C for a group of highly trained cyclists.	62
4	Time course of changes in heart rate and core temperature during 82 minutes of submaximal bicycling in the laboratory at 20°C for a group of moderately trained cyclists.	64
5	Time course of changes in heart rate and core temperature during 82 minutes of submaximal bicycling in the laboratory at 30°C for a group of moderately trained cyclists.	66

1.0. Introduction

For man to perform mechanical work, he must utilize metabolic energy to provide for muscular contraction. This energy transfer is relatively inefficient and the majority of the metabolic energy is released as heat. The heat load must be dissipated by thermoregulatory processes or core temperature will rise during exercise in moderate or hot environments. Some elevation in core temperature probably facilitates exercise performance by increasing the rate of enzyme activity, increasing nerve conduction velocity, and decreasing viscoelastic resistance in the muscle (Carlile, 1956; Martin et al., 1975; Bergh and Ekblom, 1979; Inger and Stromme, 1979). More prolonged or intense exercise produces higher core temperatures. The critical core temperature before integrated functional cellular response is lost is considered to be about 42°C (Knochel, 1974; Shibolet et al., 1976; Greenleaf, 1979; Hanson, 1979), Core temperatures in excess of 42°C are extreme and rarely observed. Even during prolonged exercise in the heat, core temperature is normally regulated at lower levels. Burke (1979) reported several cases of non-fatal heat exhaustion during a bicycle competition held under extreme environmental heat stress conditions. He speculated that prolonged road cycling can produce rectal temperatures above 40°C, but reported no data for core temperature during cycling. Bernheim (1960)

described the fatal collapse of a cyclist during competition. In this case, however, the observed dehydration and elevated core temperature (43°C) seemed secondary to amphetamine consumption in producing the fatality. Shibolet (1976) attributed the collapse of three Danish cyclists in the 1960 Rome Olympics to heat stroke. Undoubtedly, heat stress may be induced by prolonged cycling at very high ambient temperatures (e.g., 40°C). Whether a cyclist's health or performance is liable to be compromised during competitions at more moderate temperatures is unknown. The effect of different clothing on the thermal balance of a cyclist exercising in the heat has similarly not been studied systematically. The high air velocities experienced by the cyclist on the road may greatly enhance cooling rate, yet most laboratory studies have apparently ignored this factor. These issues relating to thermoregulation during prolonged submaximal bicycling at moderate or hot ambient temperature were the subject of the present investigation.

1.1. Thermoregulation in exercise:

1.1.1. Core temperature:

Core temperature has been demonstrated (Saltin and Hermansen, 1966; Saltin, 1979) to be more closely related to relative metabolic rate (oxygen uptake/maximal oxygen uptake)

than to the absolute metabolic rate (oxygen uptake) for both arm and leg exercise (Asmussen and Nielsen, 1947). The relationship between core temperature and relative metabolic rate is apparently independent of ambient temperature for a wide range of environmental conditions (Nielsen, M., 1938; Nielsen, B., 1966; Nielsen, M., 1979). In more extreme conditions, core temperature rises to a new higher level or may continue to rise throughout exercise (Wyndham, 1973).

Steady state levels of core temperature commonly average 38°C to 40°C for work rates of 70% of maximal oxygen uptake ($\dot{V}O_2$ max). Rectal temperature averaged 38.1°C and 38.6°C in a group of fit, heat-acclimatized males and females after 40 minutes of treadmill running at 50% $\dot{V}O_2$ max at ambient temperatures of 23°C and 39°C, respectively (Wells, 1980). Rectal temperature after 80 minutes of treadmill running at 70% $\dot{V}O_2$ max averaged 39.7°C for a group of trained runners (Sawka et al., 1979). Hanson (1979) reported that core temperatures of 39°C to 40.5°C were common following 60 minutes of running at 75% $\dot{V}O_2$ max, but did not provide data to support this assertion. Aikas et al., (1962) exercised trained male subjects on a bicycle ergometer for 30 minutes at each of three different work rates. Steady state levels of esophageal temperature were proportional to work rate, with a mean core temperature of 39°C at 250 W. The maximal work capacity of these subjects is not reported, so it is not possible to determine what relative metabolic rate ($\dot{V}O_2 / \dot{V}O_2$ max) these subjects maintained during this experiment. For a mixed

group of male and female subjects with large differences in $\dot{V}O_2$ max, esophageal temperature following 60 minutes of bicycle ergometry at three different submaximal work rates was proportional to the relative but not the absolute metabolic rate (Saltin and Hermansen, 1966). A work rate which required 2.98 litres of oxygen $\cdot \text{min}^{-1}$, 69% of the mean $\dot{V}O_2$ max for these subjects, was associated with a steady state esophageal temperature of 38.5°C (Saltin and Hermansen, 1966). Core temperatures in excess of 40°C have been reported following marathon running (Pugh et al., 1967; Wyndham and Strydom, 1969; Adams et al., 1978).

Esophageal temperature plateaus within 15 to 20 minutes from the onset of submaximal work in males and females (Aikas et al., 1962; Nielsen and Nielsen, 1962; Saltin and Hermansen, 1966). Rectal temperature responds more slowly, but stabilizes within about 40 minutes (Saltin, 1979). Rectal temperature may take longer to stabilize during exercise at higher relative metabolic rates. During bicycle ergometer work at 40% $\dot{V}O_2$ max, rectal temperature increased linearly for the first 40 minutes then plateaued at 37.8°C . At 68% $\dot{V}O_2$ max, rectal temperature continued to increase linearly for the entire 60 minutes of exercise for these subjects, and was 38.7°C at the end of exercise (Genovely and Stamford, 1982).

1.1.2. Sweating:

The normal thermoregulatory response to exercise involves increased circulatory and sudomotor (sweat gland) activity. Cutaneous vasodilation increases skin blood flow, which increases the rate of both convective and conductive heat transfer. Sweat glands are stimulated, thus discharging their secretion on to the surface of the skin, from where it may be evaporated (Stolwijk et al., 1977). Heat loss of $0.58 \text{ kcal} \cdot \text{g}^{-1}$ water (see Appendix 1 for abbreviations and conversions of units) is thus removed from the body (Adolph et al., 1947). Sweat rates of one to two litres $\cdot \text{h}^{-1}$ have been reported during moderately heavy exercise, even in relatively temperate conditions (Adolph et al., 1947; Saltin, 1964a; Myhre et al., 1982). Sweat is a dilute solution of electrolytes (e.g., Na^+ , K^+ , Cl^- , Mg^{+2}) and lactate, and is hypotonic with respect to plasma (Robinson and Robinson, 1954). Therefore, problems associated with excessive sweating are mainly related to water balance (Saltin, 1964b). Sweating rate is stimulated by warm skin (Nadel et al., 1971) and is suppressed by wet skin (Nadel and Stolwijk, 1973; Candas, 1979), apparently due to swelling of the epithelium and physical blockage of the active sweat glands (Kerlake, 1972). Drying the skin with a towel or by increasing ambient air velocity causes sweating rate to increase (Nadel and Stolwijk, 1973).

1.1.3. Skin blood flow:

Skin blood flow is influenced by inputs from both central and peripheral thermoreceptors (Nadel, 1980). When skin temperature is maintained at a "neutral" level during upright exercise (e.g., by clothing subjects in a rubber suit which is perfused by water of a constant temperature), skin blood flow increases in response to increasing core temperature (Brenzelmann et al., 1977). At a constant core temperature, warming the skin elicits a higher skin blood flow (Johnson and Park, 1979). The effect of core temperature on skin blood flow appears to be mediated by an active vasodilation and seems much stronger than the influence of skin temperature, which acts through decreased vasoconstrictor tone (Rowell, 1983). Skin competes with muscle for blood flow during exercise (Roberts and Wenger, 1979, 1980). At the onset of exercise, cutaneous arterioles constrict, which decreases skin blood flow. As core temperature rises, cutaneous vasoconstriction is inhibited. This directs a greater proportion of the cardiac output to the skin to increase conductive and convective cooling. Finally, in maximal exercise, cutaneous vasoconstriction is once again stimulated to permit a larger proportion of the cardiac output to be distributed to active muscle. Thus, during steady-state submaximal exercise in the heat, cutaneous blood flow increases. This decreases venous return and stroke volume and heart rate

must increase to maintain blood flow to the active muscle (Johnson et al., 1974; Rowell, 1977; Johnson and Park, 1982). Fortney et al. (1981b) measured thermoregulatory and cardiovascular responses to 30 minutes of bicycle ergometry at 60% $\dot{V}O_2$ max before and after they removed 10% of their subjects' blood volume. Skin blood flow was reduced and exercise core temperature increased following blood removal compared with the control state.

1.1.4. Dehydration:

When submaximal work is carried on for extended periods as in the present study, heart rate and core temperature seem to increase progressively during the whole period of exercise. These increases are related to body water lost due to sweating and to a lesser extent to water lost through respiration (Mitchell, J.W. et al., 1972). Pitts et al. (1944) required subjects to walk for three hours at ambient temperatures above 37°C. Rectal temperature rose steadily over the experimental session when water was withheld from subjects during exercise. If water consumption was allowed ad libitum, rectal temperature rose more slowly. When subjects were required to drink water in quantities roughly equivalent to their sweating rates, the rise in core temperature was minimal. Saltin (1964a) dehydrated subjects by up to 5% of their initial weights by heat exposure at rest. Heart rate was elevated and maximal work time decreased

in these subjects in the dehydrated condition compared to similar exercise in a normal well hydrated state. Strydom and Holdsworth (1968) exercised heat-acclimatized subjects for four hours at 45 W at high ambient temperature and humidity. As the subjects dehydrated, core temperature and heart rate increased. Wyndham and Strydom (1969) measured rectal temperature before and immediately following marathon running. Pre-exercise values of core temperature were not reported. If dehydration was less than 3% of initial body weight, rectal temperature ranged from 38.3°C to 38.9°C, and was not correlated with the extent of dehydration. Above 4% dehydration, core temperature was positively correlated with the extent of dehydration. This latter relationship was described by the equation

$$Y = 37.1 + 0.63 X$$

where Y = rectal temperature in °C

X = water deficit as a percentage
of initial body weight

(Wyndham and Strydom, 1969).

Subjects performing 60 minutes of bicycle ergometry at a mean 62% $\dot{V}O_2$ max at an ambient temperature of 22°C from whom water was withheld dehydrated about 1% of their initial body weight by the end of the exercise period. Sweating rate decreased as exercise progressed and concomittantly rectal temperature continued to increase from an apparent steady state of 37.8°C to 38.1°C by the end of exercise (Ekblom et al., 1970). Greenleaf and Castle (1971) reported that core temperature during exercise

was higher in moderately trained dehydrated subjects than in controls, while superhydrated subjects had a lower exercise core temperature than the controls. Gisolfi and Copping (1974) studied the effects of 1.5 to 2.5 hours of heavy treadmill exercise at high ambient temperatures upon a group of healthy subjects. Beyond a weight loss of 2% of initial weight, rectal temperature at the end of exercise was an average of 0.4°C higher for every 1% body weight loss. Nadel et al. (1980) used diuretics to induce an average 2.2 kg weight loss in a group of moderately trained males, who were then exercised at $55\% \dot{V}\text{O}_2 \text{ max}$ on a bicycle ergometer for 30 minutes at an ambient temperature of 35°C . Arm blood flow was lower and esophageal temperature was higher (38.8 vs 38.4°C) in dehydrated than control subjects. Fortney et al. (1981a) also used diuretics to induce a plasma volume loss in 5 males and 1 female subject. During 30 minutes of bicycle ergometer work at $65\text{-}70\% \dot{V}\text{O}_2 \text{ max}$ at 30°C , sweating rate and blood volume decrease were less than in the normally hydrated state.

Normally when body fluid is lost due to sweating, the integrity of the cell is preserved. Interstitial and blood water equilibrate, and plasma volume decreases. Hematocrit changes have been used to infer plasma volume change during exercise. But, hematocrit changes may not reflect plasma volume loss due to sweating accurately. Astrand and Saltin (1964) measured hematocrit before and after an 85 km cross-country ski race. Although subjects had lost 5.5% of their initial body weight

during the race, hematocrit measurements made one hour after completion of the race were not significantly different from pre-exercise measurements. Blood pressure and capillary permeability increase during exercise. This may cause a transient movement of plasma from blood vessels to interstitial spaces, which would cause a plasma volume change larger than that resulting from sweat loss alone (van Beaumont et al., 1973). Hematocrit following 10 minutes of progressive bicycle exercise to exhaustion was increased 4.2% packed cell volume, equivalent to a calculated plasma volume change of -13.3% (van Beaumont et al., 1972; van Beaumont et al., 1973). Similar estimates of plasma volume change were obtained for subjects performing bicycle ergometry at a work rate of 200 W. Estimates of plasma volume change made five times during 28 minutes of exercise ranged from -7.4 to -11.0% (Osness, 1968). Although sweating rate in this study may have been high, the total sweat lost during such a short period of exercise would account for only a small proportion of the calculated plasma volume change. Changes in plasma osmolality with plasma volume loss may cause error in the estimation of plasma volume loss from hematocrit reading. Sweat is hypotonic with respect to plasma. Thus, plasma becomes hyperosmolar when sweat is lost (Costill et al., 1974). This osmolarity change may cause red blood cells to shrink, which would result in a lower hematocrit reading and an underestimation of the actual plasma volume decrease (Costill et al., 1974; Harrison et al., 1975). Greenleaf et al. (1979)

support the use of hematocrit measurements for the estimation of plasma volume change. The authors acknowledge that changes in plasma osmolality may alter red cell volume, but state that for periods of exercise shorter than two hours, osmolality changes should be small and should not affect red cell volume.

Performance has been demonstrated to be impaired when the body is dehydrated as little as 2% of its initial weight (Greenleaf, 1979). Furthermore, dehydration causes inhibition of sweating in an apparent attempt to minimize any further plasma volume decrease. This results in a progressive elevation in core temperature at constant sustained work rates (Saltin, 1964a). A dehydration of more than one or two percent of total body weight results in a rise in core temperature, proportional to the extent of dehydration (Pitts et al., 1944; Strydom and Holdsworth, 1968; Wyndham, 1969; Ekblom et al., 1970; Greenleaf and Castle, 1971; Gisolfi and Copping, 1974; Nadel et al., 1980). Dehydration of 5 to 7% of body weight is associated with an increased risk of heat related disorders such as heat stroke and heat exhaustion (Adolph et al., 1947). Thirst has been reported to underestimate the extent of dehydration (Adolph et al., 1947). This finding is in agreement with unpublished data of the present investigator from a 130 km bicycle race over hilly terrain. The mean thirst rating of 20 male cyclists at the completion of the race was 5.8 (S.D. 2.1), where a rating of "one" corresponded to "not at all thirsty" and "ten" represented "extremely thirsty." Thirst rating had little relation to the

amount of fluid they reported consuming during the race ($r = -.04$). Competitors rode at an average velocity of about 37 km $\cdot h^{-1}$. Ambient temperature was about 20°C. Under these conditions, a sweating rate of approximately one litre $\cdot h^{-1}$ sustained for three and a half hours is a reasonable estimate. The mean reported fluid intake during the whole race was only 760 ml (S.D. 270 ml). Body weight was not measured. Average dehydration was calculated on the basis of subjects' reported body weight at the beginning of the race at 4% weight loss due to sweating. Because thirst may not be a reliable indicator of the extent of dehydration during exercise in the heat, it has been suggested that fluid should be consumed at frequent intervals in quantities roughly equal to the estimated sweating rate (Costill et al., 1970).

1.1.5. Circulatory changes in prolonged exercise:

Oxygen uptake, heart rate, and core temperature rise quickly at the onset of short term submaximal exercise to reach steady state values in response to increases in work rate (Saltin and Hermansen, 1966; Whipp and Wasserman, 1972; Cerreteli and Di Prampero, 1971).

In prolonged submaximal exercise, dehydration causes a reduction in plasma volume. This further compromises the already-stressed circulatory system. The resultant decreases in venous return and central blood volume produce an elevation in

heart rate to maintain cardiac output at constant submaximal work rates (Adolph et al., 1947; Kozlawski and Saltin, 1964; Saltin, 1964b; Costill et al., 1970; Costill and Sparks, 1973; Nadel and Horvath, 1977; Sawka et al., 1979). Maximal cardiac output and stroke volume appear to be relatively unaffected by dehydration. In brief exhaustive exercise, venous return is maintained by cutaneous vasoconstriction. Cardiovascular regulation has priority over temperature regulation under these conditions. Thus, in extended submaximal work, heart rate and core temperature may not stabilize, but may continue to rise throughout exercise.

1.1.6. Bicycle ergometry in the laboratory compared with actual road cycling:

Much of the empirical data regarding physiological responses to bicycle exercise have been collected from experiments with bicycle ergometry in the laboratory. A few studies have exposed subjects exercising in the laboratory to forced air flow. Nielsen (1969) directed modest airflows of $0.5-1.0 \text{ m}\cdot\text{s}^{-1}$ and $0.75-1.5 \text{ m}\cdot\text{s}^{-1}$ at the torso of subjects during bicycle ergometry and treadmill walking/running, respectively. Nadel and Stolwijk (1973) examined the effect of increasing ambient air velocity from 0.1 to $2.2 \text{ m}\cdot\text{s}^{-1}$ on sweating rate in one subject during bicycle ergometry in the laboratory. Adams et al. (1975) matched treadmill speed with a forced airflow of 4.3

$\text{m}\cdot\text{s}^{-1}$ to simulate outdoor marathon running conditions for one highly trained subject. Davies (1980) examined the effect of air flow rates of $1-7 \text{ m}\cdot\text{s}^{-1}$ on the thermoregulatory response of subjects during 60 minutes of treadmill running. Most studies of bicycling in the laboratory have not attempted to simulate the high rates of air flow experienced by the cyclist on the road. Obviously, if this factor is not fully accounted for, the physiological demands of cycling on the road and bicycle ergometry in the laboratory may not be equivalent. An enhanced rate of convective and evaporative heat loss on the road should decrease required cutaneous blood flow, thus preserving a greater proportion of cardiac output for exercising muscle. Sweat should be evaporated more completely during road cycling than during bicycle ergometry in the laboratory. Subjects performing bicycle ergometer work typically drip sweat, while road cyclists generally do not.

On the bicycle ergometer, oxygen uptake is linearly related to work rate (Pugh, 1974; Astrand and Rodahl, 1977). In cycling on the road, oxygen uptake is also directly related to work rate, when this is expressed in power output (horsepower or watts). However, drag increases as the square of velocity and overcoming drag is a major factor in the total power to cycle at typical training and competition velocities (Pugh, 1974; Firth, 1981). Thus, oxygen uptake also increases non-linearly with increasing velocity.

Firth (1981) performed a mechanical calibration on a Racer Mate ergometer and reported the following formula relating power output to calculated road speed:

$$P = 0.019 V^{2.64}, \text{ where } P = \text{power output in watts}$$

$$V = \text{cycling velocity, in km}\cdot\text{h}^{-1}$$

A small power output, constant throughout a range of velocities from 24 to 48 $\text{km}\cdot\text{h}^{-1}$, was required to turn the bicycle pedals without the Racer Mate (i.e., unloaded pedalling). An additional power output was needed to rotate the Racer Mate roller and shaft without the impellers (i.e., frictional resistance). This latter power output increased slightly with increased road velocity. At the lowest velocities studied by Firth this power output constituted approximately 30% of the total power needed to pedal the bicycle plus the Racer Mate with impellers. Drag increased as a power function of velocity. At the average cycling velocity used in the present study (37.3 $\text{km}\cdot\text{h}^{-1}$) approximately 90% of the total power was required to overcome drag.

These data compare favourably with those of other investigators. Nonweiler (1956) studied cyclists suspended on their racing bicycles in a wind tunnel. He found drag to vary as the square of air velocity. Whitt (1971) used physical principles, engineering data, and literature on the tractive

resistance offered by towed cyclists to calculate the power required to cycle at a given velocity. Total power output was determined primarily by drag and to a lesser extent by rolling resistance. Frictional resistance was considered negligible in a well-maintained racing bicycle. Rolling resistance was calculated to vary with the weight of the subject and bicycle and with tire inflation pressure. Drag was related to frontal area of the cyclist and bicycle, and to the square of cycling velocity.

Whitt (1971) made several assumptions regarding the metabolic cost of producing a given mechanical power output. The mechanical efficiency (i.e. mechanical work performed/metabolic energy required, both expressed in watts) of cycling was taken as 0.236. This value is in agreement with values of 25 and 26% reported by Wyndham et al. (1966) and Zacks (1973), respectively. The caloric equivalent of oxygen was assumed to be 5 kcal·litre⁻¹ of oxygen. For a respiratory exchange ratio of 0.95, typical of those observed in the present study, Carpenter (1948) reported a value of 4.985 for the caloric equivalent of one litre of oxygen. A power output of 0.1 hp (equal to 1.068 kcal·min⁻¹) may be calculated equivalent to 0.8544 litres of oxygen per 0.1 hp power output. Whitt (1971) rounded this value to 0.9 litres of oxygen per 0.1 hp power output.

The formulae of Whitt (1971) yield predicted oxygen costs of various cycling velocities which compare favourably with actual measurements made by other investigators. Brooke and

Davies (1973) used a Kofranyi-Michaelis respirometer to measure the oxygen uptake of racing cyclists. The metabolic cost of cycling at mean velocities of $36.6 \text{ km}\cdot\text{h}^{-1}$ on an out-and-back, mostly level course, was reported to be $1.44 \text{ kcal}\cdot\text{min}^{-1}$. This is equivalent to about $2.9 \text{ litres of oxygen}\cdot\text{min}^{-1}$. The formulae of Whitt (1971) predict a value of $2.83 \text{ litres of oxygen}\cdot\text{min}^{-1}$ for this velocity.

$$\begin{aligned} P &= (0.019)(36.6)^{2.64} \\ &= 255 \text{ W} \\ &= 0.33 \text{ hp} \\ &= 2.83 \text{ litres oxygen}\cdot\text{min}^{-1} \end{aligned}$$

Pugh (1974) measured oxygen uptake in competitive cyclists when riding at various velocities on an airport runway. An automobile rode beside the subject to collect expired gas. Oxygen uptake was reported to vary as the square of cycling velocity. A compact body position together with the technique of "drafting" (riding closely behind another cyclist) have been shown to reduce wind resistance significantly. Pugh (1976) used photographs to estimate that the "drag area" (the area which the cyclist and his bicycle present to the wind) decreased from 0.37 to 0.32 m^2 when the cyclist changed from an upright to a more crouched position. Kyle (1979) measured the rate of decrease in forward velocity when pedalling was discontinued for cyclists riding alone and in groups of varying number. He determined that the external power output required to cycle at typical racing speeds was reduced by 30% if another cyclist was followed

closely. This reduction in drag translated into an increase of 3.2 to 6.4 km·h⁻¹ in the cycling velocity which could be achieved for the same absolute metabolic rate ($\dot{V}O_2$). This allows a cyclist to maintain an equivalent riding velocity at a lower energy cost, or conversely, to achieve higher velocities at the same relative metabolic rate ($\dot{V}O_2/\dot{V}O_{2\text{ max}}$) (Kyle and Mastropalo, 1976). Jurbala (1983) measured oxygen uptake for five competitive cyclists riding on their own racing bicycles fitted with a Racer Mate. At velocities between 36 and 41 km·h⁻¹, measured values of oxygen uptake were found to compare favourably with values predicted by the formula of Firth (1981). At higher velocities (e.g., 44 km·h⁻¹), measured values of oxygen uptake were lower than predicted, which Jurbala speculated was due to the increased anaerobic contribution to higher work rates.

1.1.7. Limiting factors in prolonged submaximal exercise:

MacDougall et al. (1974) reported empirical data which suggest that hyperthermia may be a limiting factor to the continuance of prolonged heavy exercise. Subjects ran to exhaustion at approximately 70% $\dot{V}O_2$ max while wearing a vest perfused by water of different temperatures. Mean maximal work time was 91, 75 and 48 minutes for water temperatures of 18, 25 and 37°C, respectively. Rectal temperature at exhaustion in the coldest condition was lower than in the other two conditions,

suggesting that hyperthermia was not as limiting in the cold condition. In both of the warmer conditions, exhaustion was preceded by a decrease in cardiac output attributed to a decrease in stroke volume.

Trained runners, cross-country skiers and rowers have been reported to be capable of exercising at 75% of their $\dot{V}O_2$ max for several hours continuously (Astrand and Rodahl, 1977). Brooke and Davies (1973) measured the work rate of eight cyclists exercising continuously for 200 minutes in the laboratory. The work rate of 53 kJ, equivalent to an oxygen uptake of about 2.5 litres·min⁻¹ (Section 5.4), was 75% $\dot{V}O_2$ max. The report did not indicate that wind conditions were simulated or whether the cyclists consumed food or beverage (e.g., glucose solutions) during the exercise period. Higher work rates accelerate the rate of glycogen utilisation by exercising muscle (Astrand and Rodahl, 1977). Muscle glycogen was substantially depressed following 90 minutes of bicycle ergometer exercise at 77% of $\dot{V}O_2$ max (Hermansen et al., 1967). Once depleted, it takes from 24 to 48 hours to replenish glycogen stores (Hultman, 1967; Piehl, 1974).

Thus, many factors influence prolonged moderately heavy cycling effort. Surprisingly, few or no studies have addressed the practical thermoregulatory problems of competitive road cyclists either under real or simulated conditions.

1.2. Traditional cycling clothing:

Cycling clothing should be comfortable and preserve optimal thermal balance during exercise under a variety of environmental conditions. When exercising at moderate or hot ambient temperatures it may be optimal to wear as little as possible (Siple, 1949). Any clothing increases the resistance to heat flux from the body (Nagata, 1978). However, competitive cyclists are required to wear a specified type of clothing. The Canadian Cycling Association (1982) regulations state that:

"Competitor's attire shall consist of a sleeved jersey or vest and black racing shorts for the road. Socks, if worn, shall be white. Skinsuits may be worn, in which case the whole garment shall cover the rider from neck to mid thigh.... Leggings and other recognized racing attire shall be permitted in inclement weather."

It is interesting to note that this section of the regulations is titled "Appearance," suggesting the importance of clothing for visual impact rather than comfort or efficiency.

There are essentially three different sets of clothing worn during cycling. In cold wet weather, wool shorts and jersey are covered with wool or nylon leggings and a waterproof nylon windbreaker. Wool gloves may be worn. In mild weather, wool shorts and a short sleeve wool jersey are preferred. In warm weather, the shorts are usually of synthetic stretch material

such as nylon or lycra. Alternatively, in warm weather the rider wears a "skinsuit," a one-piece suit of shorts and short sleeve top of synthetic stretch material, zipped from throat to navel. Fingerless leather-palmed gloves with holes on the back of the hand, and thin leather shoes with short cotton or nylon socks usually complement any of the above garments.

The rider is required to wear a helmet, but the specifications for this item are very loosely defined. Two types of helmets are worn. The traditional "helmet" is a series of widely-spaced padded leather straps two to three cm in diameter, which would appear to offer minimal protection from impact. Riders often wear a white cotton cap over or under this helmet. Hard shell, light weight, plastic helmets are increasingly worn by competitive cyclists. The leather helmet is usually black, while the plastic helmet tends to be white. Shorts, leggings and shoes are almost always black, and the socks white, while jerseys vary widely in colour.

A cyclist's clothing is required to possess other important characteristics besides styling. It should fit closely and offer minimal drag ("wind resistance"). Research indicates that overcoming drag is a major factor in energy expenditure during cycling, especially at higher velocities (Nonweiler, 1956; Whitt, 1971; Pugh, 1974). Nonweiler (1956) determined from measurements made in a wind tunnel that drag increased by 30% when the cyclist was clothed with a jacket and flannel trousers compared with shorts and a singlet.

Clothing should also keep the rider warm in cold weather. High rates of air flow and concomittantly enhanced rates of convective heat dissipation developed while cycling often place the rider at greater risk from hyothermia than hyperthermia. The problem of selecting clothing which will protect the rider from both hypo and hyperthermia is complicated by variable weather conditions, which may change substantially during a race and by the progressive rise in core temperature normally observed during any prolonged exercise. Some riders place layers of newspaper inside the front of their clothing during cold or very windy weather, and subsequently remove successive layers of the newspaper as a race progresses and their body temperature rises or as the ambient temperature increases.

Cycling clothing is believed by racers to be an important defense against abrasions in an accident. It is undoubtedly true that any material covering the skin will offer some protection. Many accidents, however, involve the elbows and knees, which are often not covered by clothing. Therefore, it is difficult to believe that protection from abrasions is an important function of cycling clothing. Some cyclists wear wool rather than nylon shorts even in hot weather because of the extra padding the wool provides under the ischial tuberosities. One reason some cyclists prefer wool jerseys year-round is the large pockets sewn over the lumbar area. These pockets provide carrying space for water bottles and food. The high compliance of synthetic stretch fabrics has apparently discouraged attempts to sew

similar pockets on skinsuits. Finally, some racers believe that the traditional wool jersey is actually cooler than thinner synthetic stretch material because they feel the wool retains sweat at the surface of the skin, thus promoting better evaporative heat loss. Tradition, fashion, regulations, and factors other than thermal characteristics apparently influence the clothes competitive cyclists usually wear. It is not clear that traditional cycling clothes allow optimal heat dissipation while riding at moderate or warm ambient temperatures in the absence of precipitation.

1.3. Purpose of the study:

The literature on thermoregulation during exercise suggests that both dehydration and hyperthermia are potential problems in sustained submaximal bicycling. Clothing may be an important factor and light cotton garments might allow more efficient cooling during cycling at high ambient temperatures than traditional wool or lycra clothing. Yet choice of attire seems arbitrary and quite uninfluenced by systematic experimentation. Similarly, the cooling effect of the wind in actual road cycling may be substantial, yet most research on submaximal bicycling has been conducted in the laboratory where this factor has not been considered. Without simulating the high air flow rates actually encountered on the road, such studies may be characterizing the physiological demands of actual road cycling

quite incorrectly. Core temperature and heart rate seem to rise progressively during extended submaximal exercise without adequate rehydration. If these changes occur during road cycling, then heart rate will increasingly overestimate metabolic rate as exercise progresses. The degree and time course of these changes in heart rate and core temperature may be important factors contributing to performance, and it may be desirable to minimize these changes by selection of racing attire or tactics. Furthermore, measurement of heart rate is often used to infer relative metabolic rate ($\dot{V}O_2 / \dot{V}O_{2 \text{ max}}$) during cycling both on the road and in the laboratory. If heart rate increases progressively for a constant prolonged work rate, relative metabolic rate may be estimated incorrectly. The purpose of the present study was to test three hypotheses related to thermoregulation during bicycle road racing.

Hypothesis 1: Heat stress is less (as evidenced by less elevation in core temperature and heart rate, and less weight loss) during cycling at 30°C wearing cotton clothing than wearing traditional wool or lycra garments.

Hypothesis 2: Thermoregulation during conventional laboratory bicycle ergometry is different from cycling on the road because forced air

flow in the latter situation greatly enhances evaporative and convective cooling.

Hypothesis 3: Heart rate and rectal temperature increase progressively at constant work rates during simulated bicycle road racing.

2.0. Pilot studies:

2.1. Rationale:

Bicycle road races vary in length and duration. Distances of 100 to 150 km, taking three to four hours to complete, are common in North America. For the present study, it was considered impractical for motivational and attritional reasons to have subjects exercise for three hours continuously in the laboratory. It was decided instead to measure thermoregulatory responses over a shorter duration of work at the same work rate as would be maintained during longer road races. The net response over a longer race could possibly be inferred from the rate of change in physiological variables during the shorter work sessions used in the present study.

2.2. Methods:

Two pilot tests were conducted to determine the relative metabolic rate ($\dot{V}O_2 / \dot{V}O_{2 \text{ max}}$) which could be sustained for three hours of continuous bicycling. In the first pilot test, Subject #1 in this study (see Table 1 for physical characteristics of subjects) exercised on his own bicycle fitted with a Racer Mate Wind Load Simulator (Figure 1) at room temperature (24°C) with

Table 1. Physical characteristics of subjects.

Subject Number	Age ¹ (Decimal Years)	Height (cm)	Weight (kg)
1*	32.1	178	71.9
2***	24.9	202	83.2
3	28.3	173	67.1
4*	19.6	185	70.6
5	33.7	173	67.7
6	27.8	173	68.1
7	21.0	180	75.6
8	26.4	178	76.9
9*	21.3	178	74.6
10	22.3	175	63.5
11*	22.4	180	75.9
12	29.9	185	76.6
13**	23.3	170	62.5
14**	26.1	173	76.5
15**	21.0	185	86.3

Mean (+ S.D.)
for laboratory study 25.9 (± 4.8) 178 (± 4) 71.7 (± 4.6)

Mean (+ S.D.)
for all subjects 25.3 (± 4.3) 179 (± 9) 73.1 (± 6.7)

- * Participated in laboratory study only.
- ** Participated in field study only.
- *** Participated in field study and two trials in the laboratory.

¹ Age at the time of the field test

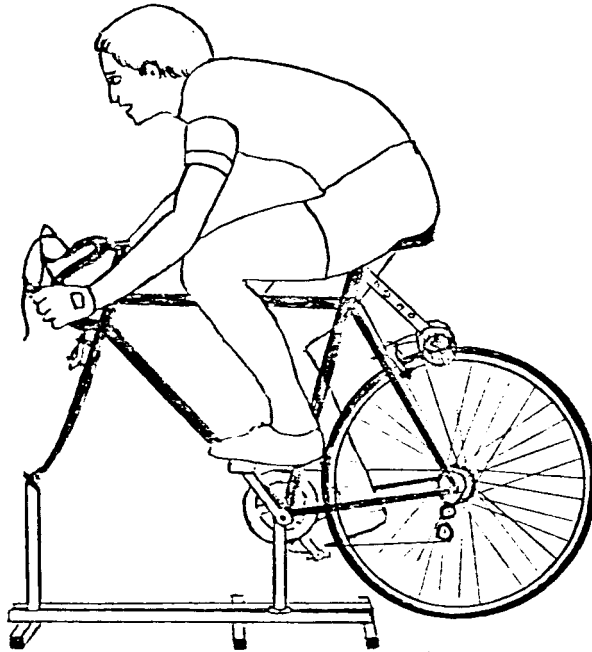


Figure 1. The experimental ergometer used in the present laboratory study, consisting of a Racer Mate Wind Load Simulator fitted to each subject's racing bicycle.

no fans or lamps for three hours in the laboratory. No food or beverage were consumed during exercise. The subject selected a pace which he believed was the highest metabolic rate he could sustain for three hours. In the second pilot study, subject #1 rode back and forth on a level straight measured 1.6 km section of road for three hours continuously. The subject consumed 400 ml of water and no food during exercise. Heart rate was measured with an Exer-Sentry digital heart rate monitor (Respironics (HK), Ltd.; Kowloon, Hong Kong) whose digital display was mounted on the handlebars. The subject recorded his heart rate every five minutes on a notepad mounted on the handlebars. Ambient temperature was approximately 20°C and the sky was clear.

2.3. Results:

For the first pilot study oxygen uptake measured during ten of every thirty minutes averaged 2.9 litres·min⁻¹. This was 60% of this subject's maximal oxygen uptake of 4.8 litres·min⁻¹ (determined one week previously, and again two days later). Pedalling frequency and oxygen uptake were very constant for the first 150 minutes of exercise. In the last 30 minutes of exercise, the subject complained of local muscle fatigue, and was unable to maintain the pedalling rate. At the end of exercise, the subject was clearly exhausted, and could not have sustained even this reduced work rate much longer. Pedalling

frequency and oxygen uptake were both about 10% lower in the last 30 minutes of exercise compared to the previous 150 minutes. Heart rate averaged $165 \text{ beats} \cdot \text{min}^{-1}$, 88% of maximal heart rate. Heart rate increased progressively during the three hours of exercise (Section 5.3.7), reaching $175 \text{ beats} \cdot \text{min}^{-1}$. However, heart rate dropped slightly during the last 30 minutes. Rectal temperature at the end of exercise was 38.9°C . The subject lost 2.50 kg, which was 3.4% of his initial body weight, during the exercise. In the second pilot study, the same subject covered 101 km in three hours of cycling on the road. Heart rate averaged $166 \text{ beats} \cdot \text{min}^{-1}$ (range 158 to $179 \text{ beats} \cdot \text{min}^{-1}$), 89% of maximal heart rate. The subject felt that he could have exercised for about another 30 minutes at this work rate, or could have maintained a slightly higher average work rate for the three hours.

2.4. Discussion:

The results of the first pilot study suggest that cardiovascular stress did not limit the subject's performance. Thermoregulatory insufficiency may have compromised performance, but as evidenced by the final rectal temperature of 38.9°C was probably not the determining factor. Depletion of muscle fuel stores may also have prevented the subject from maintaining the initial work rate throughout. No direct evidence for this conclusion was obtained, although maximal oxygen uptake measured

the day after this three-hour ride was $4.3 \text{ litres} \cdot \text{min}^{-1}$, 10% lower than the value obtained one day later or one week previously. Since the average heart rate of the subject in both pilot studies was almost identical, it was considered that relative metabolic rate ($\dot{V}O_2 / \dot{V}O_2 \text{ max}$) in the two tests was similar, although the subject was much less fatigued at the end of the road session. This apparent anomaly may be explained by two factors. First, the subject was able to vary his posture more when cycling on the road than in the laboratory, thus balancing the power output generation between more muscle groups (e.g., hamstring, gluteus). Secondly, in the interval between the two pilot tests, the subject increased his training, cycling for three hours continuously three times weekly.

2.5. Conclusion:

The first pilot test indicated that three hours of cycling in the laboratory at 65% of $\dot{V}O_2 \text{ max}$ was exhaustive. Therefore, it was estimated that 90 minutes of continuous cycling at 70% $\dot{V}O_2 \text{ max}$ in the laboratory would induce a representative dehydration and core temperature elevation without exhausting muscle energy stores. The second pilot test on the road confirmed that a work rate of about 70% of $\dot{V}O_2 \text{ max}$ could be sustained by trained cyclists for three hours of continuous road cycling since the subject felt he could have exercised at a slightly higher relative metabolic rate than that estimated in

the road test. An average velocity of $37 \text{ km}\cdot\text{h}^{-1}$ is not unusual for road races and solo time trials. Therefore, it was decided to require subjects in the major study to complete 55 km (about 90 minutes) in each laboratory session. To compare the results of these trials with actual cycling on the road, an equivalent distance was selected for the road study.

3.0. Major study:

3.1. Experimental design:

The study comprised two stages. First, a field test was conducted to study bicycling on the road. The field test was followed by a series of laboratory trials in which subjects rode a bicycle ergometer in an Environmental Chamber. In the laboratory study, each subject performed six bicycle rides, separated by approximately one week, under the conditions which simulated the presence or absence of wind velocity and hot sun wearing different riding attires, viz:

- Treatment 1 20°C, no fans or lamps, cotton clothing
- 2 20°C, fans only, cotton clothing
- 3 20°C, fans and lamps, cotton clothing
- 4 30°C, fans and lamps, cotton clothing
- 5 30°C, fans and lamps, lycra clothing
- 6 30°C, fans and lamps, wool clothing

This incomplete design was used rather than one using all 24 possible combinations of the two fan, two lamp, two temperature, and three clothing treatments because it yielded comparisons relevant to the objectives of the study and minimized the number of trials needed per subject. Treatment order was varied

non-systematically, and subjects were randomly assigned to a treatment order. It was unlikely that subjects acclimatized to the heat with only one exposure per week (Wyndham, 1973), but randomizing treatment order controlled for any slight adaptation which may have occurred.

3.2. Method:

3.2.1. Subjects:

Subjects were trained male bicyclists capable of riding continuously for 55 km at a minimum average velocity of $34 \text{ km}\cdot\text{h}^{-1}$. Eleven subjects participated in the field study. Seven of these subjects, and an additional four subjects, participated in the laboratory study. The physical characteristics of the subjects are presented in Table 1. Cyclists are ranked by the Canadian Cycling Association (1982) on the basis of their race results. The subjects in the present study ranged in ability from Category "1" (elite) to "Novice" (beginning racers). The riding categories and some cardiorespiratory attributes of subjects in the present study are presented in Table 2.

Table 2. Maximal oxygen uptake and heart rate for subjects in the present study.

Subject Number	Riding Category ¹	Maximal Heart Rate	Maximal ₁ Oxygen Uptake (l·min ⁻¹)	(ml·kg ⁻¹ ·min ⁻¹)
1	Novice	191	4.7	65
2*	2	197	5.6	69
3	4	185	4.6	68
4	3	202	4.8	68
5	4	185	4.9	73
6	Novice	200	4.1	60
7	1	195	5.5	73
8	4	202	4.8	63
9	1	192	5.9	79
10	1	195	4.8	76
11	1	175	5.2	69
12	Novice	190	5.3	69

Mean (± S.D.) 192 (± 8) 5.0 (± .5) 69 (± 6)

* Participated in only two laboratory trials; values not included in means.

¹ Category 1 are elite cyclists. Novices are cyclists in their first season of racing (Canadian Cycling Association, 1982).

3.2.2. Field study:

Subjects in this section of the main study rode eight times around a rectangular 6.9 km course on virtually flat asphalt roads in light automobile traffic. Subjects were instructed to ride at a relatively constant pace which they believed to be 70% of their maximal aerobic capacity ($\dot{V}O_2$ max). Such a pace would be somewhat faster than 70% of the maximum velocity which they could sustain for 55 km, as the required oxygen uptake increases disproportionately with increasing cycling velocity (Section 1.1.6). All subjects apparently understood the degree of effort required, but the actual $\dot{V}O_2$ max for these subjects was unknown at this point in the experiment. Subjects rode in two groups, and were permitted to ride closely together ("draft") to decrease drag. Subjects were not permitted to consume food or beverage during the ride.

Clothed body weight was determined before and after the ride on a Homs beam balance (Industrial Scales, Ltd; Vancouver, B.C.), accurate to 50 grams.

Rectal temperature was measured before and after the ride with a YSI Model 701 rectal probe (Yellow Springs Instrument Co., Inc.; Yellow Springs, Ohio) inserted approximately 15 cm into the anus. The probe was maintained in position for at least three minutes before recording the temperature displayed on a Keithley 160 Digital Multimeter (Keithley Instruments Inc.; Cleveland, Ohio). Rectal temperature was obtained within five

minutes of the completion of the ride.

Hematocrit was determined pre- and post-exercise from blood samples obtained from a fingertip puncture. The selected finger was massaged in a distal direction for approximately 30 seconds before pricking it with a sterile, disposable microlance (Becton Dickinson; Mississauga, Ontario). Blood was collected in heparinized microhematocrit tubes (Model B4415-20, American Dade, American Hospital Supply Corporation; Miami, Florida) prior to immediate centrifugation for two minutes in an Adams Readacrit microhematocrit centrifuge (Clay Adams, Becton Dickinson; Parsippany, New Jersey). Hematocrit was read with a scale and a magnifying glass to the nearest 0.5% packed cell volume. Two to four samples were obtained from each subject. The mean hematocrit for each measurement was used in all subsequent statistical analyses. Pre- and post-exercise hematocrit values were used to estimate plasma volume change (delta plasma volume) under each experimental condition using a formula described by van Beaumont (1972a):

$$\text{delta plasma volume (\%)} = 100 / (100 - A) \times 100(A - B) / B$$

where A = pre exercise hematocrit

B = post exercise hematocrit

This formula expresses the proportional change in hematocrit, thus accounting for the relatively constant red blood cell volume. A change in hematocrit from 42 to 43 % packed cell volume yields a calculated delta plasma volume of -4%.

Hematocrit was obtained within five minutes of the completion of

exercise.

Heart rate was measured continuously during exercise in each subject with an Exer-Sentry digital heart rate monitor. Dipolar dry electrodes were held in place over the chest at a point of the intersection of a line through the axilla and the fifth intercostal space by elastic straps. The liquid crystal diode display of the instrument indicating heart rate was mounted on the bicycle handlebars. Two assistants in an automobile followed the riders around the course and recorded the heart rates of the riders approximately every five minutes.

At the end of the ride, subjects were asked to rate their thirst on a 10-point scale, where "one" represented "not at all thirsty" and "ten" corresponded to "extreme thirst."

Meteorological data for the day were obtained from a nearby Environment Canada weather station.

3.2.3. Laboratory study:

3.2.3.1. Ergometry:

The type, intensity and duration of exercise in the laboratory study were designed to be comparable to the conditions of the field study. Each subject exercised on his own racing bicycle, fitted with a Racer Mate Wind Load Simulator (Racer Mate, Inc.; Seattle, Washington) as shown in Figure 1.

Conventional bicycle ergometers require the subject to work in a posture quite different from that assumed by competitive cyclists on their own bicycles. Thus the former type of cycle was not used in this study. The Racer Mate is an ergometer more appropriate for studies of competitive cyclists because it allows subjects to use their own bicycles, and simulates more closely the joint angles and muscle groups used in cycling on the road.

A stand supported the bicycle off the floor. A pair of small impellers was joined by a shaft. A 28 mm diameter, 46 mm long cylindrical aluminum roller was fixed to the middle of this shaft, and pressed on the rear tire of the bicycle. When the subject pedalled, the rear wheel rotated, causing the roller and impellers to rotate in the opposite direction, which created the drag (Firth, 1981). Work rate increased as pedalling frequency increased or as a larger pedal:wheel gear ratio was engaged. The equivalent speed of cycling on the road may thus be calculated from pedalling frequency, gear ratio and wheel diameter. A curved piece of plastic subtending an arc of 120 degrees was mounted parallel to and 25 mm from the outside of the impellers to deflect wind generated by these impellers away from the subject and thus avoid an unwanted cooling effect.

One small (3 g) magnet was screwed to a spoke on the rear wheel of the bicycle, and another similar magnet was glued to the chain ring (front sprocket). Magnetic pickups mounted on the bicycle frame detected each passage of these magnets and relayed

this information to a Pacer 2000 bicycle computer (Sportronics AG; Lucerne, Switzerland) mounted on the bicycle handlebars. The bicycle computer converted these data into pedal revolutions per minute, total distance travelled, and current and average velocities and all of these values could be presented on a liquid crystal display visible to both the subject and the experimenter. The subject was instructed to cycle 55 km at a constant pace similar to that which was maintained during the field study. Distance travelled was recorded every five minutes, and was used to calculate the average velocity over the interval.

3.2.3.2. Environmental conditions:

Environmental conditions were selected which would simulate outdoor riding conditions at warm and moderate temperatures. Laboratory studies were conducted in a 4 m x 5 m x 2.5 m high insulated environmental chamber. Temperature and humidity were maintained within $\pm 1^{\circ}\text{C}$ and $50\% \pm 10\%$ respectively, by a heating/cooling/humidifying system (Tenney Engineering, Inc.; Union, N.J.). Two large fans (Model 300, Lloyd's Porta-Dryer; Rapid City, South Dakota) were situated 80 cm in front of the bicycle handlebars. Air flow rate produced by these fans was measured with an anemometer to be $38.5 \text{ km}\cdot\text{h}^{-1}$. Radiant energy was produced by four Sylvania EBR 375-Watt movie lights (GTE Sylvania, Inc.; Salem, Massachusetts) mounted 170 cm above and

100 cm behind the subject. The rate of radiant heat produced was calculated from dry, wet and black bulb temperatures, and air flow rate, to be $678 \text{ W}\cdot\text{m}^{-2}$ (Yaglou, 1968).

3.2.3.3. Clothing:

Each item of clothing worn by the subject was weighed before and within five minutes after the completion of exercise on a Berkel balance scale (Berkel Products Co., Ltd.; Toronto, Ontario), accurate to one gram. The cotton garment consisted of white cycling shorts made of a 45% cotton/45% lycra/10% nylon material and a light-coloured cotton T-shirt. The white colour was chosen because it would absorb less of the radiant energy from the movie lamps, and thus should lower thermoregulatory demands during exercise (Forbes, 1949). The wool and lycra garments were supplied by each subject. The shorts were always black, but the colour of the jersey was not standardized. The colours used in this study were considered to be typical of cyclists' clothing worn at ambient temperatures of 30°C . Each subject wore his own cycling shoes, socks, and gloves. All subjects wore the same white plastic cycling helmet (Brancale Sport, Brancale; Italy).

3.2.3.4. Weight:

Subjects were instructed to drink and void prior to beginning each ride. They were then weighed clothed prior to the ride. After being weighed, subjects were not permitted to consume food or beverage for the duration of the trial. Clothed body weight and hematocrit were obtained pre- and post-exercise with the same apparatus and procedures as used in the field study. Nude body weight was calculated by subtracting the weight of the clothing from clothed body weight. The weight of sweat retained in the clothing at the end of exercise was calculated as the difference between the pre- and post-exercise weights of the clothing. An attempt was made to measure the mass of sweat which dripped from the subject, by placing large sheets of absorbent paper below the exercising subject. However, this was unsuccessful as the sweat evaporated from the paper too quickly in the wind from the fans.

3.2.3.5. Heart rate:

Heart rate was determined from electrocardiograph (ECG) recordings made with a Super Cardiat Century Model SCC-1A electrocardiograph (Overseas Monitor Corporation, Ltd.; Vancouver, B.C.) during the last five seconds of each minute.

Medi-Trace F23T disposable, foam-backed electrodes (Graphic Controls; Gananoque, Ontario) were applied at the left and right mid-axillary lines at the level of the nipples, and on the right scapula. Electrodes were taped in place with white athletic tape, then covered with Elastoplast waterproof plastic tape (Smith and Nephew; Lachine, Quebec). The skin was prepared by vigorous rubbing with 95% ethanol. The ECG trace was also monitored continuously on a Physio-Control Model 090-00 oscilloscope (Physio Control; Seattle, Washington).

3.2.3.6. Thermal data:

Rectal temperature was determined with an indwelling YSI 701 rectal probe inserted 15 cm into the anus, and taped in place at the base of the spine. Skin temperature was measured at the lateral calf, mid thigh, lateral upper arm, scapula, and chest with thermocouples made from HFD-30-TT 30-gauge insulated copper-constantan wire (Thermo Electric (Canada), Ltd.; Brampton, Ontario). In order to minimize disruption of normal heat flow at the skin, the welded end of each thermocouple was held to the skin with an adhesive-backed 18 x 25 mm corn plaster with a 9 mm diameter hole in the middle (Scholl (Canada), Inc.; Toronto, Ontario). The weld rested against the skin inside the hole of the corn plaster, while the wire was taped to the skin approximately 2 cm proximal to the weld. Heat flux was measured with 27.5 x 27.5 mm heat flux transducers (Thermonetics

Corporation; San Diego, California) at the mid thigh and scapula. At each site, one transducer was taped to the skin adjacent to the skin thermocouple, while another transducer was pinned to the outside of the clothing immediately adjacent to the one on the skin. Mean skin temperature was calculated from the formula described by Ramanathan (1964). Instrumenting the subject took approximately 30 minutes, and was done in the environmental chamber at the ambient temperature under which that trial was to be conducted.

All thermal data (i.e., rectal and skin temperatures, heat flux) were collected each minute by a HP 85 microprocessor interfaced with HP 3497A data acquisition/control unit (Hewlett Packard; Richmond, B.C.). A signal conditioner interfaced to the computer automatically calibrated the thermocouples by comparing their voltage outputs to an internal reference voltage representing 0°C.

A potential problem was presented by the use of the heat flux transducers. Placing a transducer over the skin may substantially alter normal heat flux in that region. The transducer almost surely has a greater resistance to heat flux than does skin. Thus, heat carried by the blood to the skin would flow more readily through surrounding tissues than through the transducer, and would leave the body around, not through, the transducer. Wissler (1982) discussed these problems in the use of heat flux transducers. Nevertheless, it was decided to use heat flux transducers in the present study to determine

whether heat flux at the body surface when exercising in the heat differed when wearing clothing made of different materials.

Heat flux transducers were calibrated by heating a 27.5 cm³ copper block with a Hewlett Packard 6218A power supply (Hewlett Packard; Parsippany, New Jersey) which supplied current to two one-Watt 15-Ohm resistors. The resistors were wired in series and placed in holes drilled through the copper block. Measurements were made at 50, 100, 150 and 200 milliamps of current. Voltage was measured simultaneously with a Fluke 8050A digital voltmeter (John Fluke Mfg. Co., Inc.; Seattle, Washington). The heat flux transducer was placed directly over the copper block. A plastic bag filled with one litre of water was placed over the transducer to hold it in place, and to serve as a heat sink. The copper block was insulated in an 8 cm³ block of styrofoam. The spaces between the copper and the foam, between the copper and the resistors, and between the copper and the transducer were filled with Wakefield Type 120 thermal joint compound (Wakefield Engineering, Inc.; Wakefield, Massachusetts). Each transducer was allowed to equilibrate for at least 90 minutes at each new current setting before the output voltage was read on the Data Acquisition Unit. Voltage readings were stable to 0.01 mV. The relationship between heat supplied and voltage output determined with this calibration device was linear over the range measured (1.1 to 16.1 mV; 107 to 1,619 W·m⁻²). The heat flux calibration factor was determined to be 105 W·m⁻²·mV⁻¹.

3.2.3.7. Oxygen uptake:

The subject wore noseclips and breathed through a two-way valve for determination of oxygen uptake for five of every fifteen minutes during exercise. The subject breathed air from the environmental chamber through 35 mm diameter Collins tubing (Warren E. Collins; Boston, Massachusetts). A Hewlett Packard Model 2107 EB pneumotach connected to a Hewlett Packard model 47304A flow transducer measured inspired air flow rate. Expired gas was directed to a two-litre plexiglass mixing box, from which oxygen and carbon dioxide concentrations were determined by S-3A and CD-3A analyzers, respectively (Applied Electrochemistry, Inc.; Sunnyvale, California). Another HP 85 microprocessor and 3497A data acquisition unit controlled the sampling and analysis of expired gas. The instruments were located outside the Environmental Chamber, and were connected to the mouthpiece with approximately 5 m lengths of Collins tubing, producing a system response time of approximately 40 seconds. The first minute of each gas collection period was used to flush the system (containing approximately 7 litres of gas). Throughout the remaining four minutes, ventilation, carbon dioxide production and oxygen uptake were monitored continuously. The oxygen uptake system was calibrated twice daily, or before each test conducted at a different ambient temperature. This method of measuring oxygen uptake was

validated by Legge (1983), who observed a high correlation ($r=0.97$) between maximal oxygen uptake as measured with the computerized system used in the present study and as measured with the classical Douglas bag technique. The ambient partial pressures of oxygen and carbon dioxide in the environmental chamber equalled those in room air outside the chamber.

Two minutes after the completion of exercise, subjects were asked to rate their thirst on the same 10-point scale previously used in the field study.

3.2.4. Maximal aerobic capacity:

During the two months of trials in the laboratory, each subject performed one short exhaustive ride to determine his maximal oxygen uptake ($\dot{V}O_2$ max). Tests were conducted at room temperature (20°C to 23°C) using the same ergometer and the same system for determining oxygen uptake used in the other laboratory trials in this study. The Collins tubing was shortened to one meter to decrease system response time to 10 seconds. At least two days separated measurement of a subject's $\dot{V}O_2$ max from any routine 55-km ride in the environmental chamber.

Subjects were weighed and ECG electrodes were attached as previously described. Subjects then warmed up for ten minutes to heart rates of approximately $140 \text{ beats}\cdot\text{min}^{-1}$. The subject stopped briefly for insertion of the mouthpiece and attachment

of the noseclip and then rode to exhaustion for a period of between five to ten minutes. During this time the work rate was increased by approximately 10% per minute by increasing pedalling frequency and/or increasing front:rear gear ratio. Maximal oxygen uptake was defined as the highest rate of oxygen consumption sustained for one minute.

3.2.5. Data entry and analysis:

3.2.5.1. Data entry:

Data recorded during the experimental sessions were transcribed to data coding sheets, and were keyed into an IBM 3030 digital computer which used Michigan Terminal System (MTS) software. To minimize data entry errors, data were entered twice and compared. Inconsistencies between the two entries were checked and corrected. Data files were also inspected visually, and simple descriptive statistics (mean, minimum, maximum) for each trial were checked for missing and erroneous data. Statistical analyses were performed using the Statistical Package for Social Sciences (SPSS) and Biomedical Data Processing (BMDP) software packages.

3.2.5.2. Data analysis:

Differences between pre- and post-exercise values of weight, hematocrit and core temperature during the field study were tested with dependent t-tests (Steel and Torrie, 1980). These three variables were together considered to represent thermoregulatory response during the road ride. This thermoregulatory response was tested with Hotelling's T^2 test for dependent samples. Hotelling's T^2 test is the multivariate analogue of the t-test. In the present study, it indicated whether the mean pre-exercise scores of all of the dependent variables were significantly different from the post exercise scores when all of the dependent variables were considered together. The difference between core temperature increase for the group of subjects who rode first and those who rode later in the day was tested with an independent t-test.

Differences between the thermoregulatory responses under the different clothing/environment treatments were tested with multiple analysis of variance (MANOVA). In this analysis, delta core temperature (i.e., the difference between rectal temperature and rectal temperature at the onset of exercise) was used to account for individual differences in resting core temperature. A repeated measures ANOVA with no grouping factor was used, as each subject was tested under all six of the clothing/environment combinations.

A MANOVA for repeated measures was also used to test the third experimental hypothesis; i.e., that core temperature and heart rate increase progressively during prolonged, steady-state simulated bicycle riding. The mean values for cycling velocity, oxygen uptake, heart rate and core temperature were calculated for three time periods of each trial; minutes 11 to 40, minutes 41 to 60, and minutes 61 to the end of exercise. These intervals were selected because the literature suggests that heart rate and oxygen uptake will reach steady state values by the tenth minute (Section 1.1.5) and that rectal temperature will stabilize by the 60th minute (Section 1.1.5) of steady state exercise. Subsequent increases in these variables would suggest a disruption of thermoregulatory and/or cardiorespiratory regulation as exercise progressed. Measurements made during the first ten minutes of exercise were omitted from this analysis because they were transients, changing rapidly prior to the attainment of the steady state measures relevant to exercise intensity before any systematic variation occurred due to thermoregulatory insufficiency. The purpose of this analysis was not to describe the adaptations to the onset of exercise, but to determine if heart rate, core temperature and oxygen uptake increased systematically during the exercise period. A two-way ANOVA was employed, with three levels of time and six levels of clothing/environment. Where the MANOVA showed significant differences between the means of dependent variables for different treatments, pre-planned comparisons of the means were

used to identify these differences. Statistical significance was accepted at an alpha level of 0.05 for all analyses.

All of the subjects were grouped together for the ANOVAs because the subjects were considered to be a relatively homogeneous group (i.e., trained male cyclists capable of riding 55 km continuously at a average velocity of at least $34 \text{ km}\cdot\text{h}^{-1}$). It was subsequently noticed that the thermoregulatory and cardiorespiratory responses of the subjects with higher measured maximal oxygen uptake ($\dot{V}O_2 \text{ max}$) were different from those subjects with lower $\dot{V}O_2 \text{ max}$. Therefore, for subsequent analyses the eleven subjects who participated in the laboratory study were classified into two subgroups on the basis of their measured maximal oxygen uptake. Five subjects each with $\dot{V}O_2 \text{ max}$ less than $69 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ were considered moderately trained, and another five subjects with $\dot{V}O_2 \text{ max}$ $69 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ or greater were classified as highly trained. The grouping criterion of $69 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ was somewhat arbitrary and two subjects classified as moderately trained had $\dot{V}O_2 \text{ max}$ of $68 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$, while one of the highly trained group measured $69 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$. However, $69 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ was a convenient group classification criterion because it produced subgroups of equal number. All of the moderately trained subjects were "Novices" or Category "3" or "4" cyclists (Table 2). Three of the highly trained subjects were Category "1" (elite) riders, but the other two highly trained subjects had limited racing experience. Maximal oxygen uptake was considered to be more appropriate than

cycling experience as a criterion for classifying subjects in the analysis of results of the laboratory studies. Mean $\dot{V}O_2$ max was $74 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ($5.3 \text{ litres}\cdot\text{min}^{-1}$) and $65 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ($4.6 \text{ litres}\cdot\text{min}^{-1}$) for the highly and moderately trained group, respectively. Subject #11 ($\dot{V}O_2$ max $69 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) was not included in either group because his measured maximal heart rate was substantially lower than the rest of the subjects, which would have artificially depressed the mean heart rate of a group in which he was included.

Time constants for the rise in core temperature and heart rate during exercise in the laboratory were determined by using non-linear regression to fit the saturation exponential equation:

$$Y = Y_{ss} (1 - e^{-kt})$$

where Y = rectal temperature or heart rate

Y_{ss} = the steady state value of rectal temperature or heart rate

t = time

k = the inverse of the time constant, tau, which is the time at which

$$Y = 2/3 Y_{ss}.$$

(Newby, 1980)

The saturation exponential equation was selected instead of other functions (e.g. linear, saturation) because it fitted the data better, as indicated by a lower residual sum of squares (i.e., the vertical distance between the smooth curve and each

data point). The best saturation exponential curve was determined for each environment/clothing condition for the first 82 minutes of exercise for highly and moderately trained subjects separately. Curves were also fitted over smaller time intervals where visual inspection of the data suggested that they might be better described by two separate exponential curves. The selection of some data for fitting by two exponential curves and the specific intervals selected for each of these two curves was made subjectively. These decisions were supported by the residual sum of squares, which were smaller for the two separate curves than for a single exponential fitted to these same data in all cases. A better overall fit might have been obtained from other combinations of exponentials, but it was considered neither practical nor more illuminating to fit separate curves to all possible combinations of time intervals. Data were analyzed separately for the moderately and highly trained subjects because of apparent differences in the thermoregulatory responses of the two groups. The differences between the exponential curves for the two groups of subjects and six environment/clothing conditions were tested with the two-sample Kolmogorov-Smirnov test (Conover, 1971). This test determines the statistical probability that the distributions of the dependent variable for the two groups in question is the same.

4.0. Results:

4.1. Maximal oxygen uptake:

Maximal oxygen uptake ($\dot{V}O_2$ max) and maximal heart rate determined for the subjects who participated in the laboratory phase of the present study are presented in Table 2. The mean value for $\dot{V}O_2$ max was 4.97 litres·min⁻¹ (S.D. 0.5 litres·min⁻¹) and that of maximal heart rate was 192 beats·min⁻¹ (S.D. 8 beats·min⁻¹). The maximal heart rate obtained for Subject #11 was only 175 beats·min⁻¹. This was considered to be a maximal value for this subject because at the end of the maximal oxygen uptake test in the present study his oxygen uptake plateaued despite an increase in work rate, which indicates that he had reached his maximal oxygen uptake. Heart rate is usually nearly maximal under these conditions (Astrand and Rodahl, 1977). Also, a similar value for maximal heart rate was obtained for this subject during three maximal oxygen uptake tests in the previous year (Legge, 1983). The mean maximal heart rate and oxygen uptake for the other ten subjects, excluding subject #11, was 194 beats·min⁻¹ (S.D. 6 beats·min⁻¹) and 4.94 litres·min⁻¹ (S.D. 0.5 litres·min⁻¹), respectively.

4.2. Field study:

4.2.1. Average cycling velocity:

Ambient temperature was 15°C (dry bulb) at 1200 hours when the first group of cyclists began riding. By 1430 hours when the second group started, the temperature had dropped to 14°C, and the sky had become overcast. The wind was steady at about 16 km·h⁻¹, and humidity averaged 59%. The Category "1" and "2" (elite) riders forming the first group completed 55 km in a mean of 88.2 minutes (range 88.0 to 88.2), or an average cycling velocity of 37.4 km·h⁻¹. Category "3" and "4" (good) riders who formed the second group were less fit and less experienced at riding closely together in a group. They completed the course in a mean time of 97.9 minutes (range 95.5 to 108.8 minutes), a mean cycling velocity of 33.7 km·h⁻¹.

4.2.2. Heart rate:

Individual heart rates of the eleven subjects in the field study ranged from 130 to 180 beats·min⁻¹ during the ride. Mean heart rate was 154 and 168 beats·min⁻¹ for the elite and good riders, respectively. Heart rate was about 10 beats·min⁻¹ higher when recorded while the rider was leading the riding group than when he dropped back to take shelter behind another rider. Mean

heart rate during the 10th to 30th minute of exercise was 150 and 160 beats·min⁻¹ for the elite and good cyclists, respectively. The combined mean for all subjects during this period was 159 beats·min⁻¹.

4.2.3. Thermoregulatory response:

Mean pre- and post-exercise values of weight, hematocrit and rectal temperature for all riders combined are presented in Table 3. Rectal temperature increased significantly ($p < 0.05$) from a mean of 36.3°C before exercise to 37.8°C following exercise. Mean weight loss was 1.5 kg, or 2.0% of initial weight. All eleven of the subjects demonstrated a significant ($p < 0.0005$) body weight loss ranging from 0.8 to 1.8 kg, or 1.1 to 2.7% of initial body weight during the ride. Mean hematocrit increased from 45.6 (S.D. 3.2) before the ride to 47.1% packed cell volume (S.D. 3.0) at the completion of the ride. The direction of the hematocrit change was not consistent, and pre- and post- exercise mean values were not significantly different. Hotelling's T^2 test indicated that a significant ($p < 0.0005$) thermoregulatory response was elicited by the road ride. The t-values obtained from the separate t-tests for each dependent variable revealed that weight loss was the predominant feature of this thermoregulatory response.

The mean thirst rating for both groups of riders combined was 5.2 (S.D. 1.8). Thirst rating was poorly correlated with

Table 3. Physiological measures in a mixed group of 5 elite and 6 good male cyclists aged 21-33 yrs, before and after a 55 km ride on the road (mean \pm S.D.).

	Pre-exercise	Post-exercise
Weight (kg)	73.5 \pm 7.6	72.0 \pm 7.5**
Hematocrit (% packed cell volume)	45.6 \pm 3.2	47.1 \pm 3.0
Rectal temperature (°C)	36.3 \pm 0.8	37.8 \pm 1.2*
Thirst rating ¹	-----	5.2 \pm 1.8

* Significantly (p<0.05) different.

** Significantly (p<0.0005) different.

¹ "1" = "not thirsty;" "10" = "extremely thirsty"

body weight loss in kg ($r=0.11$) or as a percentage of initial body weight ($r=0.12$).

The group of elite cyclists had a greater mean rectal temperature increase than the group of good cyclists. Differences between pre-exercise rectal temperature for the first group ($T_{re} = 36.2^{\circ}\text{C}$) which rode under sunny conditions and the second group ($T_{re} = 36.5^{\circ}\text{C}$), for whom the sky was overcast, were not significant. However, after exercise, the mean rectal temperature for the first group ($T_{re} = 38.4^{\circ}\text{C}$) was significantly ($p<0.05$) higher than the mean value for the second group ($T_{re} = 37^{\circ}\text{C}$). This was despite the fact that the second group exercised at a higher average heart rate. The smaller rise in core temperature for the second group depressed the average increase in core temperature for the pooled data of the two groups.

4.3. Laboratory study:

4.3.1. Cycling velocity, oxygen uptake and ventilation:

The time taken to cycle 55 km in the laboratory averaged 88.4 minutes (range 80.5 to 101.8 minutes; S.D. 4.2 minutes). Thus, velocity averaged $37.3 \text{ km}\cdot\text{h}^{-1}$. In the laboratory, riding times were generally shorter than on the road. This was probably because in the laboratory, an aerodynamic position on the bicycle and the skill of riding closely behind another rider

were unable to be practiced.

One subject (#6) was able to complete only 51 km (90 minutes) of cycling in the laboratory on his first trial. His average oxygen uptake of $2.84 \text{ litres} \cdot \text{min}^{-1}$ and average heart rate of $157 \text{ beats} \cdot \text{min}^{-1}$ were 69 and 79% of their maximal values, respectively. This subject identified leg fatigue as the predisposing factor causing termination of exercise. On five subsequent trials in the laboratory, this subject completed 55 km by moderating his cycling velocity and his $\dot{V}O_2$ ranged from 2.4 to $2.7 \text{ litres} \cdot \text{min}^{-1}$ (59 to 66% $\dot{V}O_2 \text{ max}$).

Subject #10 on his first laboratory trial cycled 55 km at an average oxygen uptake of $4.5 \text{ litres} \cdot \text{min}^{-1}$, 94% of his $\dot{V}O_2 \text{ max}$. Heart rate was $170 \text{ beats} \cdot \text{min}^{-1}$ after the first 10 minutes of exercise, and was $190 \text{ beats} \cdot \text{min}^{-1}$ at the end of exercise. The subject was very uncomfortable at this very high work rate and was exhausted at the end of the exercise. On the subsequent laboratory trials, he rode at an average $\dot{V}O_2$ of only 2.9 to $3.4 \text{ litres} \cdot \text{min}^{-1}$ (60 to 71% $\dot{V}O_2 \text{ max}$).

Mean values for oxygen uptake measured at six intervals during the approximately 90 minutes of continuous cycling in the laboratory for highly and moderately trained subjects under the six different environment/clothing conditions are shown in Figures 2 to 5. The obtained values of $\dot{V}O_2$ probably are also representative of the $\dot{V}O_2$ during the intervening periods when respired gas was not collected, as there was minimal difference in cycling velocity or heart rate between the periods when

Figure 2. Time course of changes in heart rate and core temperature during 82 minutes of submaximal bicycling in the laboratory at 20°C for a group of highly trained cyclists.

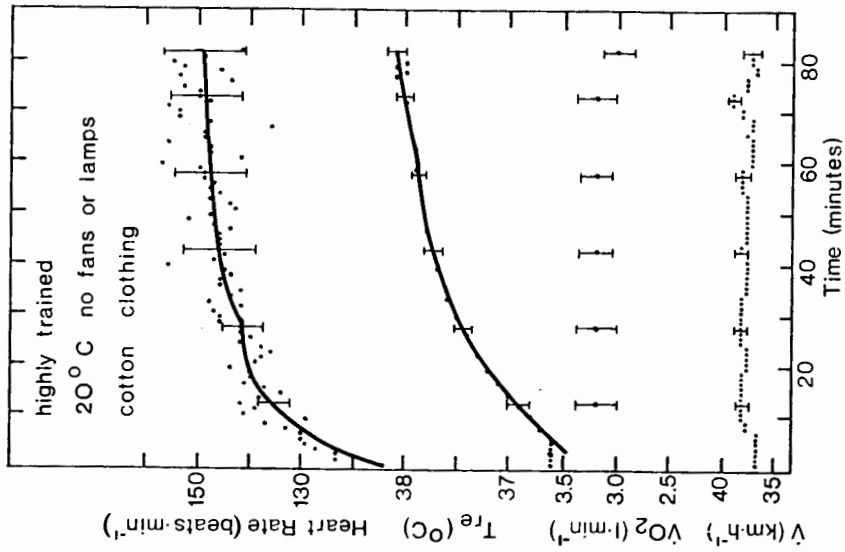
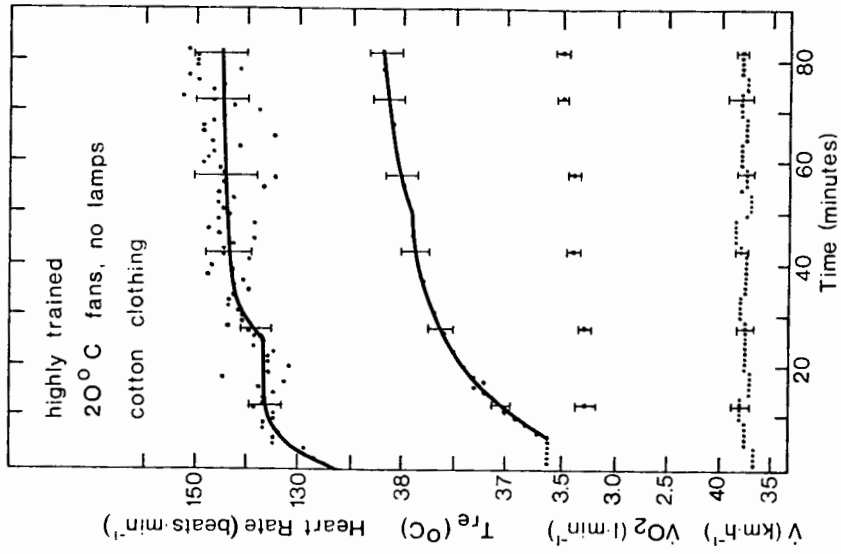
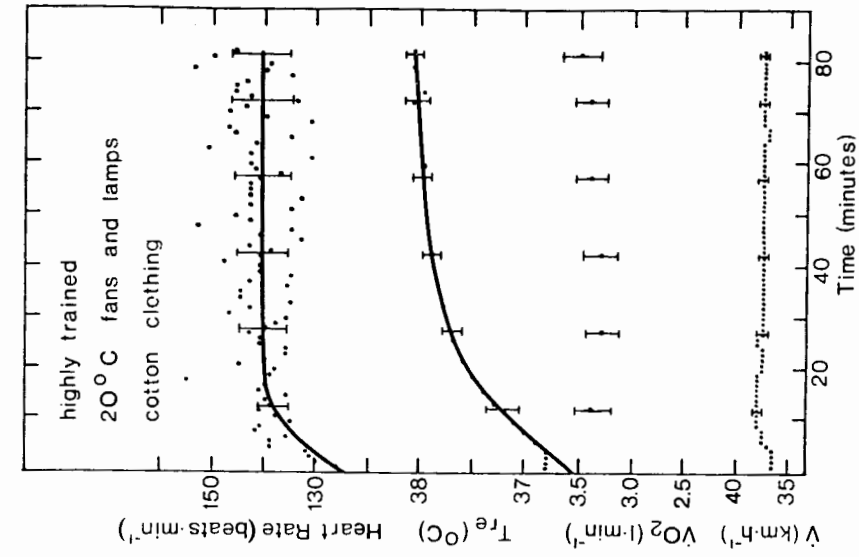


Figure 3. Time course of changes in heart rate and core temperature during 82 minutes of submaximal bicycling in the laboratory at 30°C for a group of highly trained cyclists.

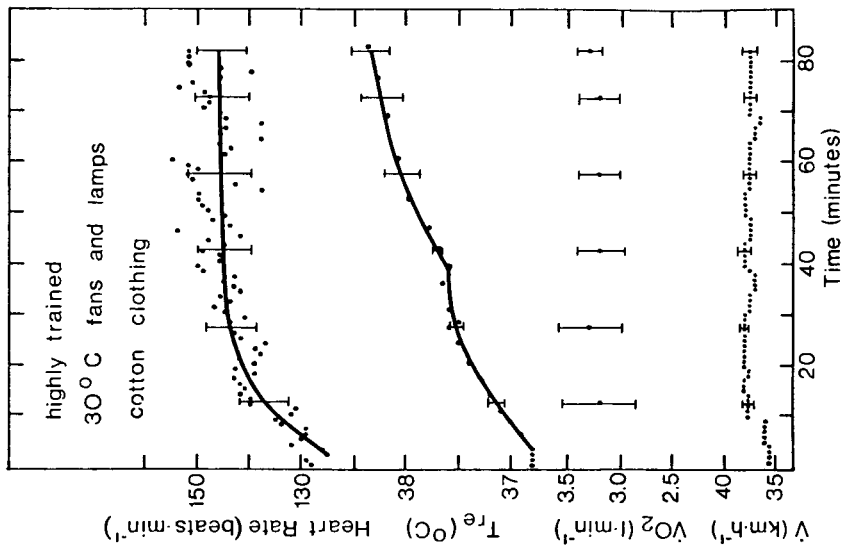
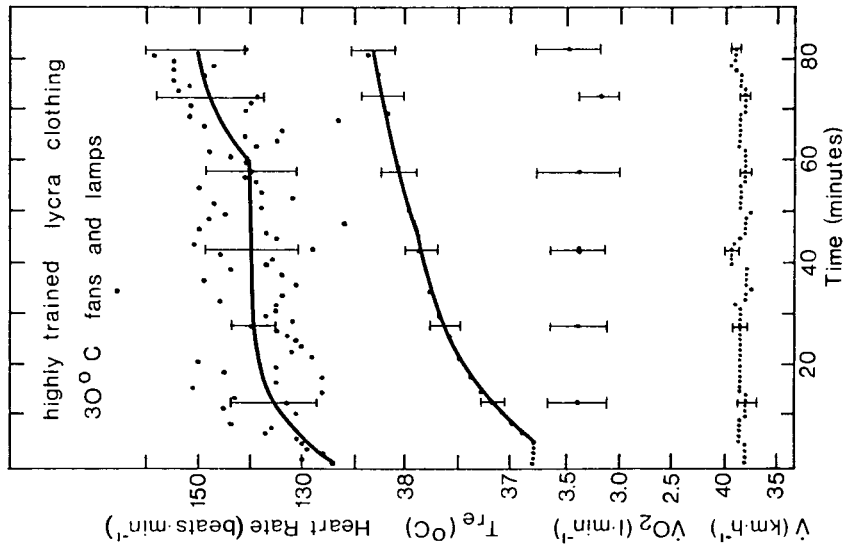
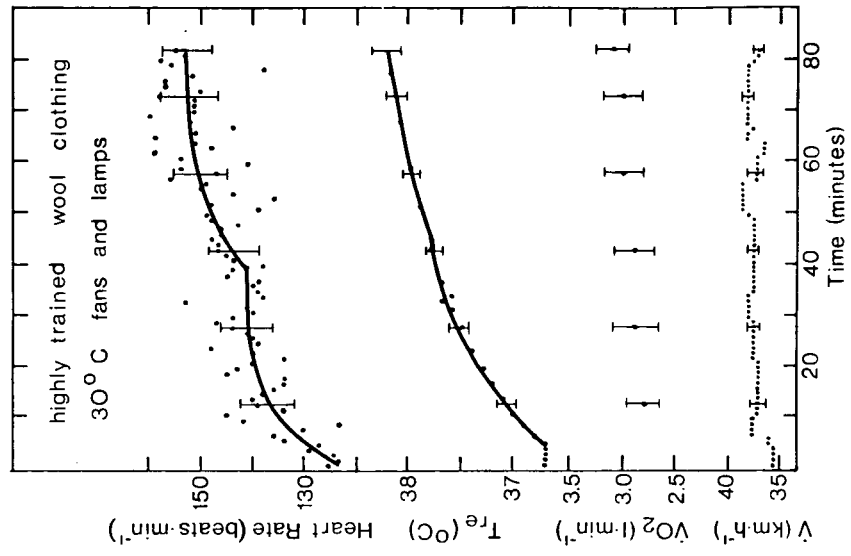


Figure 4. Time course of changes in heart rate and core temperature during 82 minutes of submaximal bicycling in the laboratory at 20°C for a group of moderately trained cyclists.

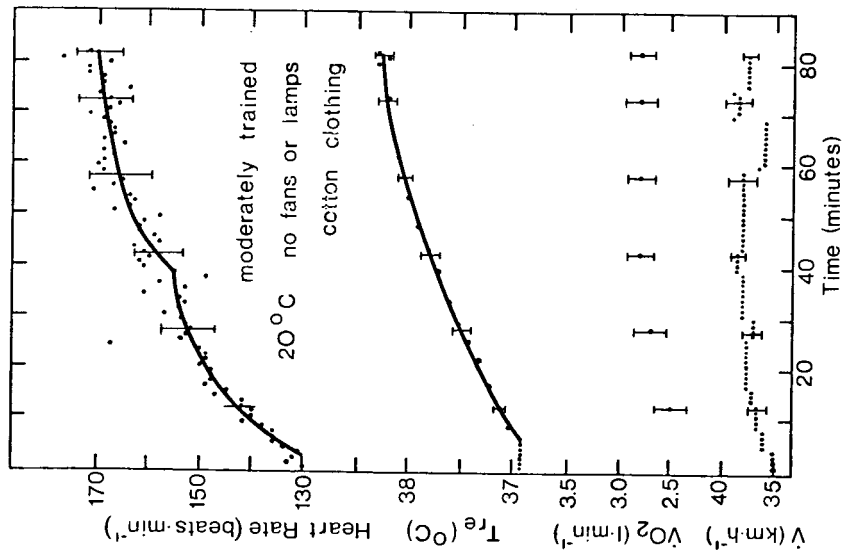
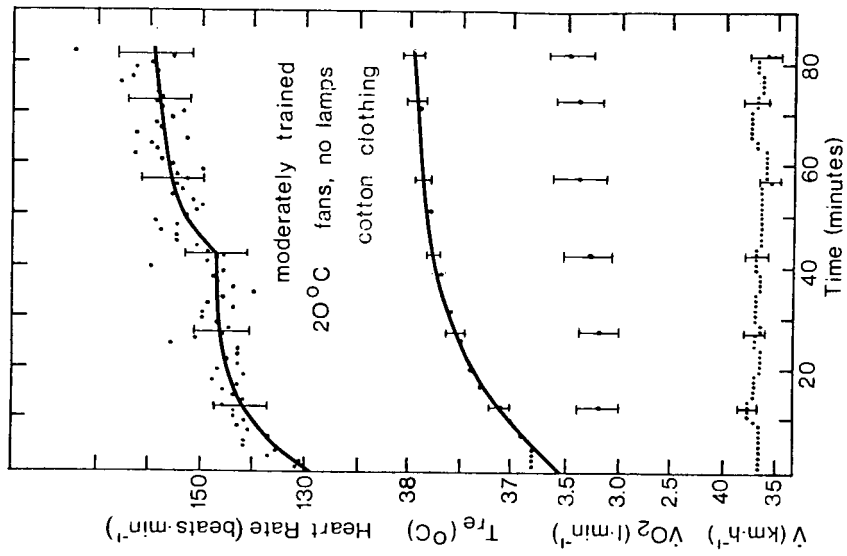
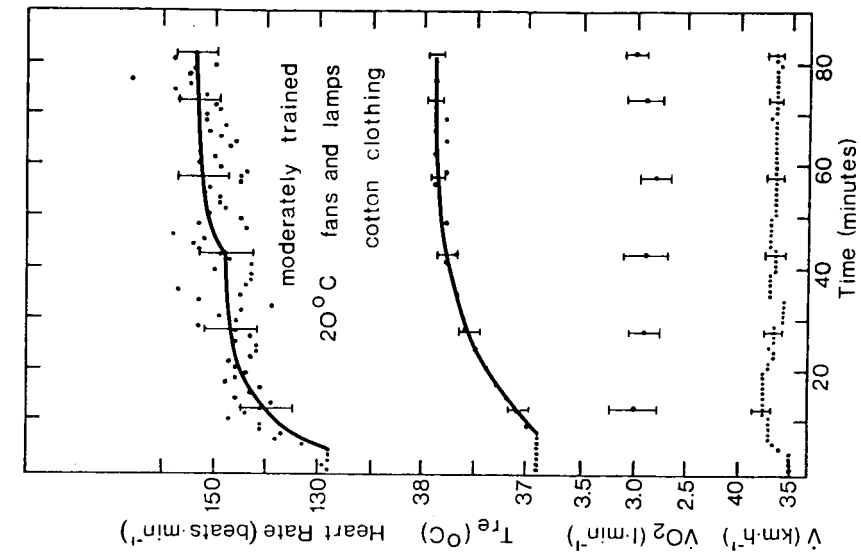
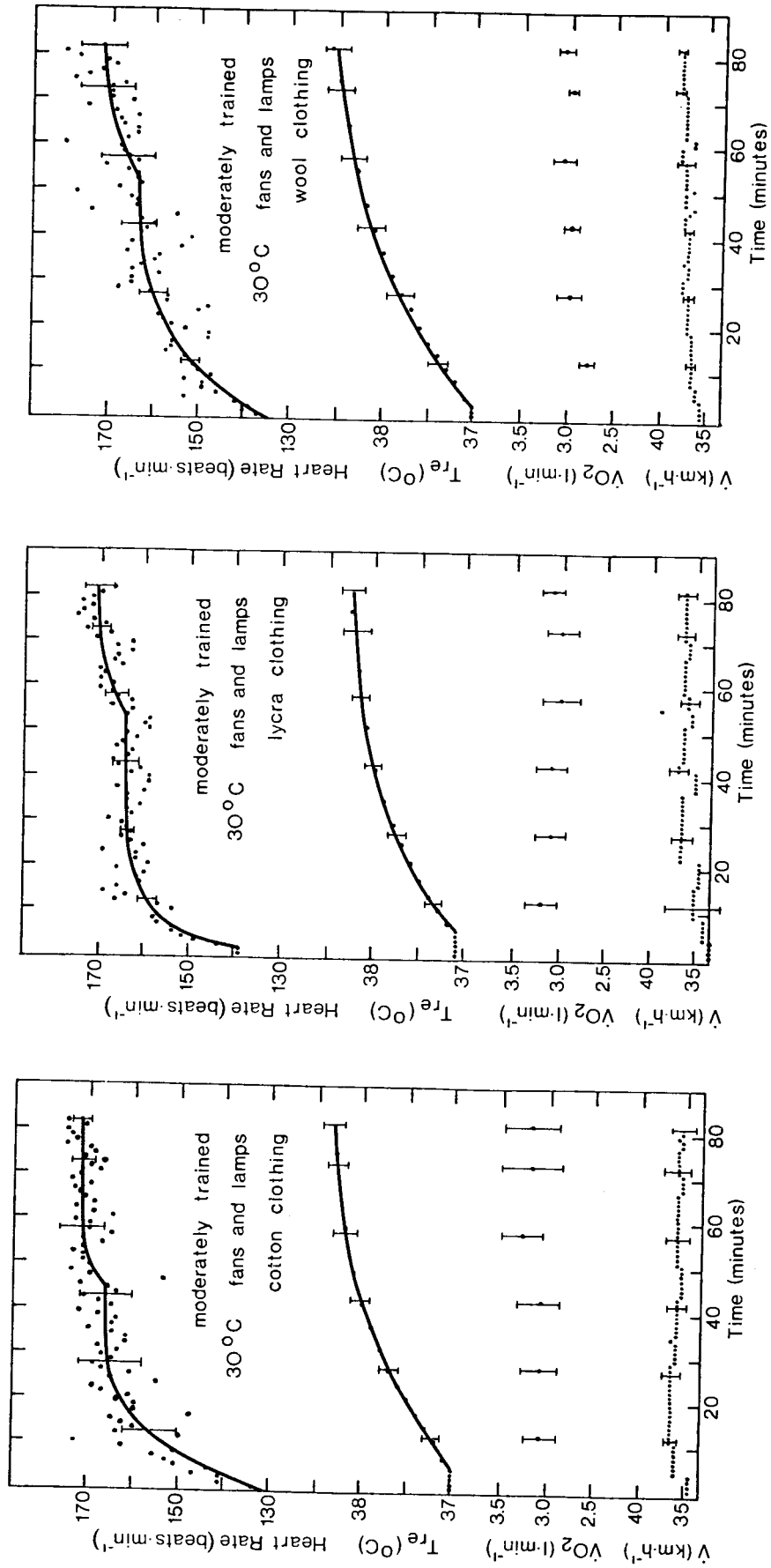


Figure 5. Time course of changes in heart rate and core temperature during 82 minutes of submaximal bicycling in the laboratory at 30°C for a group of moderately trained cyclists.



ventilation was measured or not. Mean oxygen uptake for all subjects and all clothing/environment conditions was 3.23 litres $\cdot\text{min}^{-1}$ (S.D. 0.5 litres $\cdot\text{min}^{-1}$), which was 65% of mean maximal oxygen uptake for these subjects. The mean oxygen uptake for minutes 10 to 30 for all trials conducted at 20°C and for only those seven subjects who also participated in the field study was 3.15 litres $\cdot\text{min}^{-1}$ (S.D. 0.5 litres $\cdot\text{min}^{-1}$), 65% of the mean $\dot{V}O_2$ max for this subgroup.

Minute ventilation (\dot{V}_E) was positively correlated ($r=0.87$ and 0.93 for highly and moderately trained subjects, respectively) with oxygen uptake during the 55 km of continuous cycling in the laboratory. Time dependent changes in \dot{V}_E are not presented in Figures 2 to 5 because \dot{V}_E closely paralleled $\dot{V}O_2$, but the relationship between mean values of \dot{V}_E and $\dot{V}O_2$ for both groups of subjects and each environment/clothing condition are shown in Table 4. Ventilation was similar for the highly and moderately trained subjects for most environment/clothing conditions, although $\dot{V}O_2$ was generally 10-20% higher for the highly trained group because of their faster mean cycling velocity. Oxygen uptake was similar and \dot{V}_E was 12-14% higher for the moderately trained group when cycling in cotton clothing at 20°C with the fans only (Treatment 2) and at 30°C with both fans and lamps (Treatment 4). Thus, $\dot{V}_E/\dot{V}O_2$ was consistently lower for the highly trained cyclists. This finding is also evident in the equations for the regression of $\dot{V}O_2$ with \dot{V}_E :

Table 4. Showing the relationship between oxygen uptake and ventilation for 5 moderately and 5 highly trained cyclists during 55 km of continuous cycling in the laboratory under various environment/clothing conditions (mean \pm S.D.).

		$\dot{V}O_2$ ($l \cdot \text{min}^{-1}$, STPD)	\dot{V}_E ($l \cdot \text{min}^{-1}$, STPD)
Highly trained			
Treatment	1	3.2 \pm 0.4	55.9 \pm 7.4
"	2	3.4 \pm 0.1	58.7 \pm 2.6
"	3	3.4 \pm 0.4	59.6 \pm 9.4
"	4	3.2 \pm 0.5	57.6 \pm 11.9
"	5	3.4 \pm 0.6	61.8 \pm 12.3
"	6	3.4 \pm 0.4	64.0 \pm 10.0
Moderately trained			
Treatment	1	2.7 \pm 0.3	54.8 \pm 7.2
"	2	3.3 \pm 0.5	66.6 \pm 7.8
"	3	2.9 \pm 0.3	57.5 \pm 5.8
"	4	3.2 \pm 0.5	64.4 \pm 11.4
"	5	3.1 \pm 0.3	61.2 \pm 7.9
"	6	3.0 \pm 0.2	61.6 \pm 4.8
Treatment	1	20°C cotton clothing no fans or lamps	
"	2	20°C cotton clothing fans only	
"	3	20°C cotton clothing fans and lamps	
"	4	30°C cotton clothing fans and lamps	
"	5	30°C lycra clothing fans and lamps	
"	6	30°C wool clothing fans and lamps	

highly trained: $\dot{V}_E = (19.5 \cdot \dot{V}O_2) - 5.4$

moderately trained: $\dot{V}_E = (19.2 \cdot \dot{V}O_2) + 2.8$

The relationship between oxygen uptake and mean cycling velocity in the laboratory study is shown in Table 5. Because of the decreasing oxygen cost of a given riding velocity for each rider as the experiment progressed, only data from each subject's first trial have been used. Actual values are compared to the predicted oxygen cost calculated from each subject's average velocity using the formulae proposed by Whitt (1971). The oxygen cost of unloaded pedalling was assumed to be 0.4 litres·min⁻¹ (Pugh, 1974; Lollgen et al., 1980). As previously stated, oxygen uptake for a given cycling velocity decreased significantly as the study progressed. This progressive decrease in the energy cost of a given velocity during the period of the experiment was initially considered to result from increased riding efficiency. However, subsequent analysis indicated that wear on the drive roller of the experimental ergometer was at least partially responsible for the observed decrease in oxygen uptake (Section 5.4).

4.3.2. Heart rate:

Heart rate increased rapidly at the onset of exercise (Figures 2 to 5). The mean heart rate for all eleven subjects in the laboratory study recorded between the 10th to the 30th minute of exercise for all laboratory trials conducted at 20°C

Table 5. Comparison of observed with predicted values of oxygen uptake on the Racer Mate Wind Load Simulator for a mixed group of elite and good cyclists (age 19-33 yrs) during 55 km of cycling at a relatively constant velocity in the laboratory. Results are for one trial for each subject, at various environment/clothing conditions.

Subject Number	Average Cycling ₁ Velocity (km·h ⁻¹)	Oxygen Uptake (l·min ⁻¹)	
		Predicted*	Observed
1	37.5	3.5	3.5
2	35.2	3.0	3.2
3	37.8	3.6	3.3
4	34.7	2.9	3.4
5	33.7	2.8	2.8
6	37.6	3.5	3.5
7	34.0	2.8	3.2
8	36.5	3.3	4.1
9	40.3	4.2	4.5
10	37.1	3.4	3.8
11	36.6	3.3	4.0

* From Whitt (1971) and Firth (1981). See text for formulae used to predict oxygen uptake for a given cycling velocity.

was $140 \text{ beats} \cdot \text{min}^{-1}$ (S.D. $13 \text{ beats} \cdot \text{min}^{-1}$). This was 73% of the mean maximal heart rate for this group. Mean heart rate for the seven subjects who participated in both the laboratory and field study, during the same interval and under similar conditions was $141 \text{ beats} \cdot \text{min}^{-1}$ (S.D. $9 \text{ beats} \cdot \text{min}^{-1}$), 73% of the mean maximal heart rate for this subgroup. Thus, heart rate response to exercise was similar for both the subgroup and the whole group during this exercise period. Mean heart rate for the eleventh to the last minute of exercise for all subjects and all environment/clothing conditions combined was $150 \text{ beats} \cdot \text{min}^{-1}$ (S.D. $16 \text{ beats} \cdot \text{min}^{-1}$).

4.3.3. Time dependent changes in core temperature, heart rate, and oxygen uptake during prolonged steady-state bicycle exercise:

Mean values for cycling velocity, core temperature, heart rate, and oxygen uptake calculated for all subjects and clothing/environment conditions combined, for three specified time intervals throughout exercise (minutes 11 to 40, minutes 41 to 60, and minutes 61 to the end of exercise) are shown in Table 6. Mean cycling velocity did not change significantly throughout the 55 km of each laboratory session. Despite maintenance of a relatively constant external power output, the group mean core temperature and heart rate increased significantly ($p < 0.001$) between each of the three time intervals.

Table 6. Progressive increases in core temperature and heart rate through three specified time intervals in a mixed group of elite and good cyclists (age 19-33 yrs) while cycling 55 km in the laboratory. Results for three trials at 20°C and three trials at 30°C for each subject are combined (mean \pm S.D.).

	minutes 11 to 40	minutes 41 to 60	minutes 60 to end of exercise
Velocity (km·h ⁻¹)	37.5 \pm 2.0	37.5 \pm 1.8	37.5 \pm 1.8
Oxygen uptake (litres·min ⁻¹)	3.16 \pm 0.46*	3.23 \pm 0.45*	3.27 \pm 0.45*
Rectal temperature (°C)	37.5 \pm 0.2**	37.9 \pm 0.3**	38.1 \pm 0.3**
Heart rate (beats·min ⁻¹)	143 \pm 15 **	149 \pm 16 **	153 \pm 15**

* Significantly (p<0.05) different from both other time intervals.

** Significantly (p<0.001) different from both other time intervals.

Oxygen uptake also increased significantly ($p < 0.05$) between all three time intervals. The interaction between oxygen uptake ($\dot{V}O_2$) and treatment approached significance. This indicated that the observed increase in $\dot{V}O_2$ during the experiment was different for different treatments. Further analysis showed that $\dot{V}O_2$ rose significantly ($p < 0.05$ to $p < 0.0005$) throughout successive designated time intervals during rides wearing cotton at 20°C under simulated wind conditions but no radiant heat load (Treatment 2), and while wearing wool clothing at 30°C with simulated wind and radiant heat load (Treatment 6). Changes in $\dot{V}O_2$ were not significantly different between any of the specified time periods for any of the other environment/clothing conditions.

4.3.4. Differences in thermoregulatory responses to prolonged submaximal bicycling in the laboratory between highly trained and moderately trained cyclists:

Time-dependent changes in the mean values of heart rate, rectal temperature, oxygen uptake and cycling velocity for the highly trained group for each of the six environment/clothing conditions in the laboratory study are illustrated in Figures 2 and 3. Comparable mean data for the moderately trained cyclists are shown in Figures 4 and 5. Although the mean time to cycle 55 km was 88 minutes (range 81 to 102 minutes), only the first 82 minutes of exercise have been included in this analysis to

prevent the scores of the subjects who cycled at a slower average velocity from influencing the mean values for the final minutes of exercise excessively. Time constants for the response of heart rate and core temperature to the onset of work are presented in Tables 7 and 8 and the level of significance of the differences between these responses for the moderately and highly trained subjects under various environment/clothing conditions are presented in Table 9.

The highly trained subjects rode generally faster than their less well trained counterparts, with the exception of the rides performed at 30°C wearing wool clothing (Treatment 6), in which cycling velocity was similar for the two groups. The highly trained group also rode at a more constant velocity for the duration of each exercise session. Absolute metabolic rate ($\dot{V}O_2$) was generally higher for the highly trained group (mean $\dot{V}O_2$ 3.3 litres·min⁻¹ for all environment/clothing conditions combined) than for the moderately trained group (3.0 litres·min⁻¹) as shown in Table 4. When riding at 30°C wearing wool clothing (Treatment 6), $\dot{V}O_2$ and velocity were similar for the two groups. During rides at both 20°C wearing cotton clothing with fans but no lamps (Treatment 2) and at 30°C wearing cotton clothing with both fans and lamps (Treatment 4) mean $\dot{V}O_2$ was similar for the two groups, although the highly trained group cycled faster under these conditions. Relative metabolic rate ($\dot{V}O_2/\dot{V}O_{2\text{ max}}$) for all environment/clothing conditions combined was lower for the highly trained than for the

Table 7. Time constants for the exponential increase in rectal temperature following the onset of 55 km of cycling in the laboratory for moderately and highly trained cyclists under various environment/clothing conditions.

	Highly Trained			Moderately Trained		
	time interval (min)	time constant (min)	residual sum of squares	time interval (min)	time constant (min)	residual sum of squares
Treatment 1	6-82	27	.10	7-82	56	.12
	6-61	28	.06			
	62-82	200	.02			
Treatment 2	6-82	21	.15	6-82	23	.09
	6-50	17	.05			
	50-82		.03			
Treatment 3	4-82	19	.10	8-82	19	.10
Treatment 4	5-82	53	.35	5-82	38	.11
	5-38	24	.03			
	39-82	90	.14			
Treatment 5	5-82	31	.18	6-82	31	.07
	5-46	23	.04			
	47-82	48	.06			
Treatment 6	5-82	35	.11	3-82	59	.16
	5-45	30	.05			
	47-82	→ ∞	.05			

Treatment 1 20°C cotton clothing no fans or lamps
 2 20°C cotton clothing fans only
 3 20°C cotton clothing fans and lamps
 4 30°C cotton clothing fans and lamps
 5 30°C lycra clothing fans and lamps
 6 30°C wool clothing fans and lamps

Table 8. Time constants for the exponential increase in heart rate following the onset of 55 km of cycling in the laboratory for moderately and highly trained cyclists under various environment/clothing conditions.

	Highly Trained			Moderately Trained		
	time interval (min)	time constant (min)	residual sum of squares	time interval (min)	time constant (min)	residual sum of squares
Treatment 1	1-82	11	1347	1-82	38	735
	1-28	5	199	1-38	24	417
	29-82	$\rightarrow \infty$	840	39-82	15	311
Treatment 2	1-82	19	1117	1-82	45	1423
				1-42	8	493
				43-82	45	610
Treatment 3	1-82	4	1913	1-82	17	1420
				1-41	10	567
				41-82	15	863
Treatment 4	1-82	21	1067	1-82	10	1670
				1-43	10	949
				44-82	5	457
Treatment 5	1-82	27	6894	1-82	7	1172
	1-60	10	5226	1-53	5	437
	61-82	$\rightarrow \infty$	1353	54-82	40	223
Treatment 6	1-82	32	2061	1-82	28	1841
	1-40	11	780	1-53	18	1209
	41-82	59	1038	54-82	$\rightarrow \infty$	473

Treatment 1 20°C cotton clothing no fans or lamps
 2 20°C cotton clothing fans only
 3 20°C cotton clothing fans and lamps
 4 30°C cotton clothing fans and lamps
 5 30°C lycra clothing fans and lamps
 6 30°C wool clothing fans and lamps

Table 9. Showing the significance of the difference between rectal temperature and heart rate responses for moderately and highly trained subjects for various environment/clothing conditions. Values are the probability that the two curves being compared are identical.

	Rectal Temperature	Heart Rate
Moderately vs highly trained		
Treatment 1	.005 *	<.0005 *
" 2	<.0005 *	<.0005 *
" 3	<.0005 *	<.0005 *
" 4	.059	<.0005 *
" 5	.576	<.0005 *
" 6	<.0005 *	<.0005 *
Moderately trained		
Treatments 1 vs 2	<.0005 *	<.0005 *
" 1 vs 3	<.0005 *	<.0005 *
" 2 vs 3	.998	.003
" 3 vs 4	<.0005 *	<.0005 *
" 4 vs 5	.926	.003 *
" 4 vs 6	.003 *	.005 *
" 5 vs 6	.003 *	.059
Highly trained		
Treatments 1 vs 2	.038 *	.059
" 1 vs 3	.024	<.0005 *
" 2 vs 3	.254	.059
" 3 vs 4	.038 *	.001 *
" 4 vs 5	.129	.001 *
" 4 vs 6	.707	.452
" 5 vs 6	.576	.003 *

* Significant at the 0.05 level or greater.

Treatment 1	20°C cotton clothing no fans or lamps
2	20°C cotton clothing fans only
3	20°C cotton clothing fans and lamps
4	30°C cotton clothing fans and lamps
5	30°C lycra clothing fans and lamps
6	30°C wool clothing fans and lamps

moderately trained group (62 vs 65% $\dot{V}O_2$ max). Mean relative metabolic rate varied less between different environment/clothing conditions for the highly trained than the moderately trained group (range 60 to 64 vs 59 to 72% $\dot{V}O_2$ max).

In all six environment/clothing conditions, mean core temperature at the beginning of exercise was lower for the highly trained group, and in all conditions except when riding at 20°C with fans and lamps (Treatment 3), core temperature for this group was observed to approach a steady state but then began rising again as exercise was continued. Core temperature for the moderately trained group rose more steadily throughout exercise. Mean core temperature at the 82nd minute of exercise was lower for the highly trained than the moderately trained group only when riding at 20°C wearing cotton clothing with no fans or lamps (Treatment 1) and at 30°C wearing wool clothing with fans and lamps (Treatment 6), and was higher for the highly trained group under the other environment/clothing conditions. Time constants for the rise in core temperature following the onset of exercise were identical for the two groups while exercising at 20°C with fans and lamps while wearing cotton clothing (Treatment 3) but the curves for the two groups were still significantly different ($p < .0005$) as shown in Table 10 because the initial core temperature was higher for the moderately trained group. Core temperature response was not significantly different between the moderately and highly trained subjects when riding at 30°C wearing lycra clothing

(Treatment 5). Data for the highly trained subjects for this condition were fitted with a double exponential curve, and the time constant for the first curve was shorter than the time constant for the moderately trained subjects. However, the subsequent rise in core temperature for the highly trained group under these conditions was slower, thus the core temperature response for the two groups of subjects over the 82 minutes of exercise was not significantly different. Time constants for the rise in core temperature were shorter ($p < .005$) for the highly trained than for the moderately trained group for the other four environment/clothing conditions.

Mean heart rate was lower at the beginning of and throughout exercise for the highly trained group under all environment/clothing conditions. Heart rate appeared to approach a steady state value then rose again as exercise progressed for both groups of subjects under most environment/clothing conditions, but the attainment of temporary steady state heart rate generally occurred earlier for the highly trained subjects. Time constants for the response of heart rate to the onset of steady state work were shorter for the highly trained subjects at 20°C with no fans or lamps while wearing cotton clothing (Treatment 1), at 20°C with both fans and lamps while wearing cotton clothing (Treatment 3) and at 30°C with fans and lamps while wearing wool clothing (Treatment 6). Time constants for the rise in heart rate were shorter for the moderately trained subjects for the other three environment/clothing conditions.

Heart rate response was significantly ($p < .0005$) different between the moderately and highly trained subjects for all six environment/clothing conditions (Table 9).

The saturation exponential curve fitted rectal temperature data very well, as indicated by the consistently very low residual sum of squares. Residual sums of squares were very much larger for the exponential fit of the heart rate data. Fitting these data with two separate curves for time intervals selected from visual inspection of the plotted data yielded a lower residual sum of squares in all cases where these separate curves were fitted. The second exponential curve usually had a much longer time constant which in several cases approached infinity, indicating that the rise in heart rate or core temperature in the latter portion of exercise was minimal.

4.3.5. Thermoregulation at 20°C ambient conditions with and without simulated radiant heat gain and wind velocity:

Thermoregulatory responses during bicycling under standard laboratory conditions (i.e., no wind or sun) were different from simulated bicycling on the road (i.e., with fans producing forced air flow rates comparable to those experienced on the road at these cycling velocities). Mean values for physiological variables measured under these conditions are shown in Table 10. Delta core temperature was the difference in rectal temperature between the last and first minutes of exercise. Delta plasma

Table 10. Thermoregulatory responses in a mixed group of elite and good cyclists (age 19-33 yrs) while cycling 55 km in the laboratory at 20°C under standard laboratory conditions and under simulated road cycling conditions (mean \pm S.D.).

	standard laboratory (no fans or lamps)	simulated road "overcast" (fans only)	"sunny" (fans and lamps)
Cycling velocity (km·h ⁻¹)	37.7 \pm 1.7	37.4 \pm 2.0	37.4 \pm 1.5
Oxygen uptake (l·min ⁻¹)	2.9 \pm 0.4	3.3 \pm 0.3	3.2 \pm 0.4
Delta core temperature (°C)	1.4 \pm 0.4	1.4 \pm 0.5	1.2 \pm 0.3
Mean skin temperature (°C)	34.3 \pm 1.5**	30.4 \pm 1.0	29.6 \pm 2.1
Heart rate _{-1,1} (beats·min ⁻¹)	156 \pm 19	151 \pm 15	146 \pm 13
Body weight loss (% of initial weight)	2.4 \pm 0.6*	1.8 \pm 0.4	1.8 \pm 0.5
Delta plasma volume (%)	-7.1 \pm 6.6	-6.3 \pm 4.5	-6.3 \pm 4.5
Weight of sweat retained in clothing (g)	300 \pm 157**	42 \pm 32	36 \pm 28
Thirst rating (1=low,10=high)	5.0 \pm 1.7	3.5 \pm 1.9	4.4 \pm 1.2

¹ Mean of minutes 61 to end of exercise.

* Significantly (p<0.01) different from both other conditions.

** Significantly (p<0.0005) different from both other conditions.

volume was the change in plasma volume calculated from pre and post exercise measurements of hematocrit. Mean cycling velocity, oxygen uptake, delta core temperature, delta plasma volume and thirst did not differ significantly between rides performed under these three different environmental conditions. Mean skin temperature ($p < 0.0005$), body weight loss ($p < 0.01$), and the weight of sweat retained in the clothing at the end of exercise ($p < 0.0005$) were significantly greater under laboratory than under simulated road riding conditions. There was a trend toward higher heart rate without the fans, but this was not significant ($p = .06$). There were no significant differences in the attained steady state of the physiological variables between rides performed either under simulated sunny (i.e., fans and lamps) and overcast (fans only) conditions.

The effect of the wind and radiant heat load during laboratory simulations of actual road cycling may also be studied by comparing thermoregulatory responses for both highly trained (Figure 2) and moderately trained cyclists (Figure 4) while riding at 20°C with the fans and lamps (Treatment 3), with the fans only (Treatment 2), or with neither fans or lamps (Treatment 1). Subjects wore cotton clothing under all three of these environmental conditions. Riding velocity was similar in all three conditions, but oxygen uptake ($\dot{V}O_2$) was lower during Treatment 1 than under the other two conditions. Core temperature was similar at the beginning of exercise in both groups of subjects for all three environmental conditions. The

highly trained group mean core temperature rose more gradually as exercise progressed when riding without the fans and lamps (Treatment 1) than during the other two conditions, but began increasing again from steady state levels near the end of exercise and was similar at the 82nd minute of exercise under all three environmental conditions. Core temperature failed to reach a steady state, continued to rise throughout exercise, and reached much higher final values for the moderately trained group during Treatment 1 than under the other two environmental conditions. Heart rate was initially similar for all three environmental conditions, but rose more quickly and to higher levels during Treatment 1. Heart rate response during Treatment 1 was significantly ($p < .0005$) different from both other environment/clothing conditions for the moderately trained subjects, and significantly ($p < .0005$) different from Treatment 3 (both fans and lamps) for the highly trained group. Differences in heart rate response during Treatments 1 and 2 (fans only) for the highly trained group approached significance ($p < .06$). The differences in heart rate between Treatment 1 and rides under the other two environmental conditions were more pronounced for the moderately trained than the highly trained group. Core temperature response while riding with the fans only (Treatment 2) and with both the fans and lamps (Treatment 3) were similar for both groups of subjects, but heart rate response during these two conditions was different ($p < .005$) for the moderately trained subjects and approached significance ($p < .06$) for the

highly trained group.

4.3.6. Thermoregulatory responses wearing different garments at 30°C:

The mean value of several physiological variables measured while subjects were exercising wearing three different types of clothing with simulated wind and sun at 30°C are presented in Table 11. The amount of sweat retained in the clothing was significantly ($p < 0.01$) greater when wearing wool than other clothing. Mean skin temperature was significantly ($p < 0.01$) lower while wearing cotton compared to lycra clothing. Differences in skin temperature between riding while wearing cotton and wool, or between wool and lycra were not significant. Differences in mean cycling velocity, oxygen uptake, core temperature elevation, heart rate, weight loss, plasma volume change, and thirst rating were not significantly different during rides wearing these different garments.

A comparison of the time course of changes in heart rate and core temperature while riding at 30°C with fans and lamps reveals subtle differences in the effects of the cotton, lycra and wool garments (Figures 3 and 5 and Tables 7 and 8). Oxygen uptake was higher although riding velocity was similar or lower when wearing cotton compared with wool (Section 5.3.5). Heart rate and core temperature were similar when wearing cotton compared with wool for the highly trained subjects. Core

Table 11. Variation in physiological variables related to heat stress in a mixed group of elite and good cyclists (age 19-33 yrs) according to the garments worn while cycling 55 km in the laboratory at 30°C under conditions of simulated wind and sun (mean \pm S.D.).

	cotton	lycra	wool
Cycling velocity (km·h ⁻¹)	37.0 \pm 2.1	37.5 \pm 2.3	37.2 \pm 1.3
Oxygen uptake (l·min ⁻¹)	3.2 \pm 0.5	3.2 \pm 0.5	3.3 \pm 0.4
Delta core temperature (°C)	1.5 \pm 0.4	1.5 \pm 0.4	1.5 \pm 0.5
Mean skin temperature (°C)	32.1 \pm 1.0	32.9 \pm 1.4**	32.3 \pm 1.0
Heart rate (beats·min ⁻¹) ¹	159 \pm 15	158 \pm 18	159 \pm 17
Body weight loss (% of initial weight)	2.7 \pm 0.5	2.7 \pm 0.6	2.8 \pm 0.4
Delta plasma volume (%)	-9.5 \pm 4.1	-6.0 \pm 0.6	-6.0 \pm 8.2
Weight of sweat retained in clothing (g)	87 \pm 105	65 \pm 49	159 \pm 117*
Thirst rating (1=low,10=high)	7.2 \pm 1.3	6.7 \pm 1.0	6.3 \pm 1.9

¹ Mean of minutes 61 to end of exercise.

* Significantly (p<0.01) different from both other garments.

** Significantly (p<0.001) different from cotton clothing only.

temperature rose more slowly and was lower at the 82nd minute of exercise for the moderately trained cyclists wearing cotton rather than wool ($p < .005$). Heart rate at the end of exercise was similar when wearing cotton and wool garments for these subjects. Heart rate increased more rapidly initially for the moderately trained cyclists when wearing cotton clothing ($p < .01$). Oxygen uptake and riding velocity were similar or lower when wearing cotton than lycra and the time-dependent changes in heart rate and core temperature were very similar when wearing these two garments, except that there was a very pronounced plateau and subsequent rise in core temperature when wearing cotton for the highly trained subjects ($p < .005$). Oxygen uptake was similar or higher when wearing lycra than wool. Despite the higher absolute metabolic rate ($\dot{V}O_2$), increases in core temperature and heart rate were similar or lower when wearing the lycra for both moderately and highly trained subjects.

4.3.7. Comparison of thermoregulatory responses in moderately and highly trained subjects during prolonged submaximal bicycling at 20°C and 30°C ambient temperature:

Heart rate and core temperature responses to riding wearing cotton clothing with fans and lamps were different for both highly ($p < .05$) and moderately ($p < .0005$) trained subjects at an ambient temperature of 20°C than at 30°C. Steady state values of heart rate for highly trained subjects (Figures 2 and 3) were

higher at 30°C. Heart rate rose rapidly and was much higher throughout exercise at 30°C for the moderately trained subjects (Figures 4 and 5). Heart rate reached a temporary steady state value but began rising again after about 40 minutes of exercise for these subjects at both 20 and 30°C. Core temperature rose more quickly initially at 20°C than at 30°C for the highly trained group. At 30°C, however, core temperature approached an asymptote but then began rising steadily at the 40th minute of exercise for these subjects. Core temperature approached a steady state value which was lower after 82 minutes of exercise at 20°C than at 30°C for both moderately and highly trained subjects.

Mean core temperature for all environment/clothing conditions combined was significantly correlated ($p < 0.02$) with relative metabolic rate ($\dot{V}O_2 / \dot{V}O_{2 \text{ max}}$), but this correlation was low ($r = 0.25$). The correlation between rectal temperature and absolute metabolic rate ($\dot{V}O_2$) was even lower and was not significant ($r = 0.11$). The relationships between core temperature and relative and absolute work rate respectively for each separate environment/clothing condition were inconsistent, and correlation coefficients for these comparisons were generally small and non-significant.

4.3.8. Hematocrit:

Average resting hematocrit was 45.2% packed cell volume (S.D. 2.7) but there was considerable variability among repeated measurements for each subject (Table 12). Hematocrit for all subjects and environment/clothing conditions combined increased to a mean of 47.1 (S.D. 2.8) following exercise, and the calculated plasma volume decreased by 6.9% (S.D. 5.6%).

4.3.9. Thirst:

The mean thirst rating for all subjects and all environment/clothing conditions combined was 5.2 (S.D. 2.0). Mean body weight loss was 1.7 kg (S.D. 0.4 kg), which was 2.4% (S.D. 0.63%) of initial body weight. Subjects' perception of their thirst was only moderately but significantly correlated with the extent of their dehydration, expressed as total weight lost ($r=0.54$) or as a percentage of their initial body weight ($r=0.52$).

To facilitate comparison of the laboratory results with results from the field study, the relationship between thirst rating and dehydration was determined for the two environment/clothing conditions in the laboratory which were most similar to the environmental conditions on the day of the road ride. The mean thirst rating for laboratory rides at 20°C wearing cotton clothing with the fans only (Treatment 2) and

Table 12. Variability in pre-exercise hematocrit readings (%) for a group of trained male cyclists (age 19-33 yrs) measured on six separate occasions at approximately one week intervals. Values are mean packed cell volume for two to four samples from each subject on each occasion.

Subject Number	Trial						Mean \pm S.D.
	1	2	3	4	5	6	
1	40.0	45.7	46.0	44.9	43.8	43.5	44.0 \pm 2.2
3	43.8	46.3	47.8	44.5	47.3	46.5	46.0 \pm 1.6
4	49.0	46.3	48.3	49.5	44.0	48.5	47.6 \pm 2.1
5	40.5	42.7	43.7	42.3	42.5	40.3	42.0 \pm 1.3
6	43.5	45.8	48.2	46.0	47.0	46.0	46.1 \pm 1.6
7	49.2	46.3	46.2	46.3	42.0	42.0	45.3 \pm 2.8
8	49.0	48.5	44.3	48.5	51.2	48.5	48.3 \pm 2.2
9	46.5	46.8	48.7	46.2	47.3	46.5	47.0 \pm 0.9
10	42.1	44.3	41.0	41.5	42.1	42.3	42.2 \pm 1.1
11	46.0	48.5	44.3	45.2	46.0	48.2	46.4 \pm 1.7
12	42.3	42.0	42.8	44.3	40.5	42.0	42.3 \pm 1.2
Mean \pm S.D.	44.7	45.7	45.6	45.4	44.9	44.9	
	3.4	2.1	2.5	2.4	3.2	3.0	

with both the fans and lamps (Treatment 3) was 3.9 (S.D. 1.6). Mean body weight loss under these conditions was 1.3 kg (S.D. 0.3 kg), or a mean of 1.8% (S.D. 0.4%) of initial body weight.

4.3.10. Heat flux:

Heat flux transducer wires were fragile and broke frequently. The transducer pinned to the back of the clothing was malfunctional for the entire experiment. Voltage outputs were obtained for the heat flux transducers in only 79 of 198 cases (3 transducer x 11 subjects x 6 treatments). Ten of the twelve mean values for the two transducers on the thigh had a negative sign (i.e., indicating that heat was flowing toward the body). Little significance can be attached to heat flux data because of methodological problems (Section 5.11), thus these data are not presented.

4.4. Comparison of actual road cycling with simulated road riding in the lab:

A comparison of physiological and thermoregulatory responses measured for seven subjects during actual road cycling in the field study and during laboratory cycling are summarized in Table 13. Ambient temperature on the day of the field study was 14-15°C, and the sky became overcast at mid-day. These conditions were cooler than any of the laboratory conditions,

Table 13. Comparison of physiological and thermoregulatory responses in a mixed group of seven elite and good male cyclists (age 21-33 yrs) during 55 km of cycling on the road at 15°C with an equivalent distance in the laboratory at 20°C with simulated wind (mean \pm S.D.).

	Road Riding	Laboratory Riding
Velocity ¹ (km·h ⁻¹) ¹	34.5 \pm 2.2	37.1 \pm 1.6
Heart rate (bpm) ¹	158 \pm 15	141 \pm 9
Oxygen uptake (l·min ⁻¹) ¹	-----	3.15 \pm 0.5
Rectal temperature (°C)	37.3 \pm 1.1	38.1 \pm 0.3
Weight loss (kg)	1.44 \pm 0.39	1.35 \pm 0.26
(% initial weight)	2.0 \pm 0.5	1.9 \pm 0.4
Delta plasma volume (%)	-7.0 \pm 6.2	-7.3 \pm 4.3
Thirst ²	5.1 \pm 1.8	3.8 \pm 1.6

1 Average for 10th to 30th minute of exercise to minimize the effect of warmup and dehydration. Other variables measured at the end of exercise.

2 "1" = "not thirsty;" "10" = "extremely thirsty."

but were very favourable for the season and locality. The laboratory trials conducted at 20°C with fans, both with and without the lamps (Treatments 3 and 2, respectively), have been selected for comparison with the road ride. Mean cycling velocity on the road ($34.5 \pm 2.2 \text{ km}\cdot\text{h}^{-1}$) was less than in the laboratory ($37.1 \pm 1.6 \text{ km}\cdot\text{h}^{-1}$). Core temperature at the end of the 55 km ride was also on the average lower on the road ($37.1^{\circ}\text{C} \pm 1.1$) than in the laboratory ($38.1^{\circ}\text{C} \pm 0.3$). Body weight loss averaged 2.0. (S.D 0.5) and 1.9% (S.D. 0.4) of initial weight on the road and in the laboratory, respectively. Mean plasma volume change calculated from hematocrit measurements was also similar for the two conditions ($-7.0\% \pm 6.2\%$ for the road, and $-7.3\% \pm 4.3\%$ for the laboratory), although subjects were on the average more thirsty after the road ride (5.1 ± 1.8) than after similar rides in the laboratory (3.8 ± 1.6). Mean heart rate during the 10th to 30th minute of exercise was substantially greater during road cycling than cycling in the laboratory (158 vs 141 beats $\cdot \text{min}^{-1}$).

5.0. Discussion:

5.1. Maximal oxygen uptake and heart rate:

Maximal oxygen uptake of subjects in the present study was similar to values reported for other competitive male cyclists (Table 14). The mean maximal heart rate of $194 \text{ beats} \cdot \text{min}^{-1}$, for all subjects excluding Subject #11, is as expected for a group of subjects with a mean age 26 years (Astrand and Rodahl, 1977).

5.2. Road ride:

Although the elite cyclists completed 55 km on the road in less time, they rode at a substantially lower average heart rate than the group of good cyclists (Section 4.2.2). The elite group was observed to ride more closely together and to corner at higher speed. They may be able to maintain a higher average velocity at a lower absolute metabolic rate ($\dot{V}O_2$). The elite group had a higher mean $\dot{V}O_2 \text{ max}$ than the other cyclists, although the mean maximal heart rate for the two groups was similar. The $\dot{V}O_2$ /heart rate relationship was probably linear for both groups of subjects across the range of relative metabolic rates ($\dot{V}O_2 / \dot{V}O_2 \text{ max}$) imposed in the present study. The slope

Table 14. Values for maximal oxygen uptake of competitive male distance cyclists reported by other investigators.

Author	Riding Category of Subjects	$\dot{V}O_2$ max ($l \cdot \text{min}^{-1}$)
Pugh, 1974	"competitive"	4.64
Foster and Daniels, 1975	1	5.21
"	2	4.34
"	3	3.96
Nichols, 1977	1	5.30
"	2 and 3	4.98
Burke, 1980	1	5.00
Perez, 1981	1 to 3	4.78
Vrijens et al., 1982	1 to 3	4.63
White, 1982	1	4.93
present study	1 to Novice	4.97

of the $\dot{V}O_2$ /heart rate line may, however, be different for the two groups. The elite group may have actually been working at a higher $\dot{V}O_2$ despite their lower mean heart rate (Astrand and Rodahl, 1977).

The elite cyclists had a higher mean core temperature at the end of 55 km of cycling on the road than the good cyclists (Section 4.2.3). This difference was probably not the result of the slightly warmer environment in which the first group rode. Nielsen (1938, 1979) has demonstrated that exercise core temperature is relatively independent of ambient temperature for a wide range of ambient temperatures. Furthermore, the actual difference in the environmental heat load experienced by the two groups of cyclists in this study was small. The one degree C greater ambient temperature and the greater solar radiation during the time the first group rode taken together account for less than 100 W of additional heat load, less than 10% of the metabolic heat production (see Section 5.5 and Appendix 2 for relevant detailed heat balance calculations). The elite cyclists rode faster, engendering a greater rate of metabolic heat production, albeit at a lower heart rate since their maximum absolute metabolic rate was higher. The elite group was also more adept at riding more closely together to take shelter from the wind and reduce drag. In doing so they would also reduce the rate of evaporative and convective cooling, the main avenues of heat loss under the conditions of this study. Optimal performance during bicycling in the heat may be achieved by

delicate balancing of both beneficial and detrimental aspects of wind speed.

5.3. Relative metabolic rate:

During 55 km rides in the laboratory, mean oxygen uptake for the whole group of elite and good riders was 65% of the mean measured $\dot{V}O_2$ max of 4.97 litres·min⁻¹ (Section 4.3.1). As indicated in Section 1.1, heart rate rises exponentially at the onset of exercise towards an asymptote at the steady state value. In prolonged exercise, plasma volume loss and increased skin blood flow may cause a further elevation in heart rate (Section 5.6). The heart rate between the 10th to 30th minutes of exercise in the present study should have achieved steady state levels reflecting the oxygen cost of the activity and have been relatively uninfluenced by dehydration (Saltin, 1964a). In the laboratory studies, mean heart rate and oxygen uptake in a similar time period for the seven subjects participating in both the laboratory and field study were 73 and 64% of maximal values, respectively. On the road, heart rates for these subjects during the relevant time interval of the ride averaged 82% of maximal heart rate. This suggests that on the road, subjects exercised at a higher relative metabolic rate ($\dot{V}O_2 / \dot{V}O_2$ max) than they did in the laboratory, despite the fact that the average velocity on the road was lower than in the laboratory during the equivalent time period. The experimental ergometer

may have permitted a given gear ratio to be pedalled at a given pedalling frequency with less mechanical power than it would take to pedal at the equivalent cycling velocity on the road. This may have been the result of wear on the experimental ergometer (Section 5.4).

5.4. Oxygen cost of different cycling velocities:

During the first laboratory session cycling velocity ranged from 34 to 40 km·h⁻¹ and measured values of oxygen uptake were similar to the predicted oxygen cost for these velocities (Table 4). The predicted values underestimated the observed values by an average of 0.3 litres·min⁻¹, perhaps because the actual energy cost of unloaded pedalling at 100 rpm was higher than the value of 0.4 litres·min⁻¹ assumed in making these predictions. The results of the present study suggest that the oxygen cost of cycling at equivalent velocities of 34 to 40 km·h⁻¹ on the Racer Mate Wind Load Simulator in the laboratory may be estimated as

$$\dot{V}O_2 \text{ (litres}\cdot\text{min}^{-1}\text{)} = 2.1 \cdot 10^{-4} \cdot v^{2.64} + 0.7$$

where v is velocity in km·h⁻¹.

This is a tentative conclusion because oxygen uptake was measured at only one particular cycling velocity per subject over the range of velocities represented by the equation.

The Racer Mate's aluminum roller is subjected to substantial stresses during exercise. The ratio of the circumference of the roller to that of the rear wheel is 28:700

(1:25). Subjects in the present study typically pedalled at 100 revolutions per minute (rpm) at pedal:wheel gear ratios of 3.25 (e.g., 52-tooth front gear with 16-tooth rear gear). Thus, the aluminum roller may be calculated to be rotating at $25 \cdot 100 \cdot 3.25 = 8,125$ rpm.

Over the course of some 100 hours of pilot testing and experimentation, a rounded groove approximately 1 mm deep was worn in the roller. Oxygen uptake ($\dot{V}O_2$) for a given cycling velocity apparently began to decrease during later trials. At the time, this had been considered to be the result of increasing efficiency of cycling resulting from practice on the experimental ergometer. At high pedalling rates (e.g., 120 rpm during maximal oxygen uptake testing) the Racer Mate assembly bounced on the rear wheel, and had to be manually held in contact with the tire. This observed bouncing raised doubts about the effect of the roller wear at submaximal workrates. The effect of practice and/or roller wear on $\dot{V}O_2$ was tested by multiple linear regression analysis. The separate correlation of velocity and number of trials with $\dot{V}O_2$ was 0.3619 and -0.5827, respectively. In a stepwise regression carried out with $\dot{V}O_2$ as the dependent variable and velocity and number of trials as independent variables, the number of trials was a better predictor of $\dot{V}O_2$ than was velocity. When the regression procedure was forced to select velocity first, velocity accounted for only 2% of the variance in $\dot{V}O_2$, while the number of trials accounted for an additional 47% of the remaining

variance in $\dot{V}O_2$. Oxygen uptake was poorly correlated with velocity, contrary to expectation, while there was apparently some other factor or factors (e.g., practice or wear on the experimental ergometer) which were related to the decreasing $\dot{V}O_2$ observed over the course of the experiment.

As a follow up, the effect of roller wear upon the oxygen cost of cycling at a given velocity was measured. Subject #1 in the present study cycled at a relatively constant velocity of $38.0 \text{ km}\cdot\text{h}^{-1}$ on his own bicycle fitted with a Racer Mate. Following an appropriate warm up, the subject cycled for eleven minutes first with the worn roller, and then with a new one. The procedure was repeated four times; i.e., four eleven-minute work periods with the worn roller alternated with four work periods with a new roller. Oxygen uptake and heart rate were measured during the last four minutes of each work period. One-tailed t-tests for correlated samples ($df=15$) were used to test the hypothesis that oxygen uptake and heart rate were lower with the worn roller than with the new one. Oxygen uptake ($t=7.25$) and heart rate ($t=8.80$) were both significantly ($p<0.0005$) lower with the worn roller.

These findings strengthened the view that wear on the experimental ergometer allowed it to be pedalled with less effort for a given gear ratio and pedalling frequency over the course of the experiment. Thus, underestimation of $\dot{V}O_2$ from workrate on the Racer Mate may occur. In the present study $\dot{V}O_2$ was measured directly during all experiments, eliminating this

potential source of error.

5.5. Differences in thermoregulatory response to prolonged submaximal bicycling in the laboratory between highly trained and moderately trained cyclists:

The increase in rectal temperature from pre-exercise levels to its steady state level was described very well by a saturation exponential relationship (Figures 2 to 5 and Tables 7 and 9). This is consistent with the high ($r = 0.83$ to 0.97) correlations between observed and predicted values of both core temperature and heart rate during steady state work using a computer model based on a saturation exponential (Givoni and Goldman, 1972; Givoni and Goldman, 1973). Such an exponential relationship is not surprising, as core temperature change during exercise may be modelled as two first order functions coupled in series. The forcing function is the metabolic heat engendered by exercise. Heat produced in active muscle is transported by the blood and conducts directly through overlying tissues to reach the surface of the body. At the surface, heat is lost by convection, evaporation and radiation. Core temperature lags metabolic heat production, but eventually rises to a steady state level (providing the environmental and exercise conditions are not too severe), determined by the relative rates of heat gain and loss. A longer time constant for the rise in core temperature may imply less metabolic heat

production or it may represent a more efficient cooling rate under these specific environment/clothing conditions. The very low residual sum of squares for the exponential fit of the increase in rectal temperature with time during steady state submaximal exercise is probably a function of the long time delay between events in the active muscle and a change in visceral temperature; that is, the system is damped. The response of heart rate to the onset of steady state work could also be described by a saturation exponential, but the residual sum of squares was much larger than for core temperature (Table 8). This reflects the much more rapid response of heart rate to variations in external workrate, posture and respiratory pattern.

Shorter time constants for the attainment of steady state values of heart rate and oxygen uptake following an increment in workrate have been reported for more highly trained subjects (Whipp and Wasserman, 1972). In the present study, core temperature adjusted more quickly following the onset of exercise for the highly trained than for the moderately trained cyclists. This may similarly be an adaptation to training. Perhaps skin vasoconstrictor activity is more sensitive in well trained individuals. Such an adaptation would cause greater cutaneous vasoconstriction at the onset of exercise than in the less well trained under similar exercise and environmental conditions. This would allow muscle blood flow requirements to be met with a lower cardiac output and heart rate in the well

trained. As core temperature increases, initially there is no stimulation to cutaneous vasodilation, but at some critical level of core temperature, active cutaneous vasodilation increases skin blood flow. Any subsequent increase in heat transport to, and loss from, the skin would slow the rise in core temperature, thus core temperature would reach the same steady state level attained by less trained individuals under the same conditions. The attainment of steady state heart rate was not as consistently more rapid for the highly trained subjects. The hypothetical adaptation in the kinetics of core temperature increase postulated above might also explain the similar heart rate time constants observed for both highly and moderately trained riders in the present study. It might be expected that for the highly trained subjects, because of their greater training, heart rate would rise more quickly than for their moderately trained counterparts. However, the decreased skin blood flow postulated above for the highly trained group would permit the same work to be accomplished with lower initial heart rate. The net result would be similar time constants for the response of heart rate to the onset of work in both groups of subjects. This proposed adaptive effect of training could be tested by comparing the heart rate and core temperature kinetics of highly trained and moderately trained subjects exercising with cold skin (e.g., at low ambient temperature, or with a water perfused suit). Under these conditions, skin blood flow would initially be small in both groups. Similar time constants

for the response of heart rate and core temperature to the onset of work in both groups would support the hypothesis that heart rate kinetics are related to the state of physical conditioning but are masked by lower skin blood flow for the highly trained subject during the initial stages of submaximal exercise in the heat.

The failure of both groups to maintain these steady state values throughout exercise suggests that an additional stimulus is superimposed upon the forcing function of steady state work, and that this factor exerts a stronger effect as exercise is continued. There is evidence that this factor is progressive dehydration due to sweating and to a lesser extent, to respiratory water loss (Section 5.8). As expected, absolute metabolic rate ($\dot{V}O_2$) during exercise was higher for the highly trained than the moderately trained cyclists because of the higher average riding velocity of the former group. Relative metabolic rate ($\dot{V}O_2 / \dot{V}O_{2 \text{ max}}$), however, was generally lower for the highly trained group because of their superior aerobic capacity. Despite their lower mean cycling velocity, the moderately trained group had a mean oxygen uptake similar to that of the highly trained group when both groups wore cotton clothing and rode at 20°C with fans but no lamps (Treatment 2), and at 30°C with both fans and lamps (Treatment 4). The highly trained group may have been more efficient than their less well trained counterparts; i.e., they may have accomplished the same external work with less effort. The rapid phasic contraction and

relaxation of lower limb muscles required in order to cycle at 100 revolutions per minute may become smoother, and extraneous body movements may be minimized with practice. It is difficult, however, to explain why such a superior efficiency was apparent only under these two environment/clothing conditions.

Perhaps the unexpectedly high oxygen uptake for the moderately trained group under these conditions is due to a cold-induced stimulus due to wind speed which increases metabolic rate. Thermoregulatory neurons in the hypothalamus are influenced by core temperature, but they also receive neural inputs from the skin (Pierau and Wurster, 1981). Swan (1981) differentiated between body heat which is a byproduct of energy production required to perform mechanical work ("essential energetics") and heat production which is not related to muscular contraction ("non shivering thermogenesis"). Resting skeletal muscle and brown adipose tissue (BAT) are apparently the main sites of non shivering thermogenesis (NST) and are responsive to neural and hormonal stimulation (Cannon, 1981; Swan, 1981). Although BAT has traditionally been considered to be important only in neonates and adult cold adapted mammals, recent evidence also suggests a thermogenic role for BAT in heat acclimatized rats (Donhoffer, 1971) and adult man (Rothwell and Stock, 1979). In the present study, the essential energetics engendered by the exercise produced heat which caused the core temperature to rise. When exercising in cotton clothing with the fans, the very high rates of air flow may have stimulated NST, causing oxygen

consumption to rise beyond that required to perform the work of cycling. The moderately trained cyclists had less actual cycling experience, and may have responded to the unfamiliar wind with a greater NST. This explanation is speculative, and would be more convincing if disproportionately large $\dot{V}O_2$ had also been observed for the moderately trained group when riding at 20°C with both fans and lamps while wearing cotton clothing (Treatment 3). It is unlikely, though, that any single mechanism can explain what are likely quite complex and interrelated thermoregulatory and exercise responses. For example, although it is mainly aerobic (thus, oxygen-consuming) metabolism which produces energy for muscular contraction during submaximal exercise and the resultant heat dissipation raises core temperature, an elevated body temperature itself increases metabolic activity at the cellular level, which further increases oxygen consumption (Wyndham, 1973; Lehninger, 1975). In addition, the greater elevation in heart rate for the moderately trained group at 30°C would have increased myocardial oxygen consumption. Thus, although non shivering thermogenesis would seem to be an inappropriate response to exercise in the heat, it may be part of a complex thermoregulatory response to simulated bicycle road racing conditions where high wind velocities into the face of the cyclist prevail. This possibility remains to be elucidated more fully.

5.6. Differences in thermoregulatory responses during laboratory ergometry compared with simulated road riding conditions:

Subjects used visual feedback from the digital display of the bicycle computer to monitor their riding velocity, and attempted to maintain similar velocities during each laboratory, simulated road riding session. The similar average velocities while riding at 20°C wearing cotton clothing with fans and lamps (Treatment 1), with fans only (Treatment 2) and with neither fans or lamps (Treatment 3) suggests that they did not deliberately moderate their pace while riding without the fans and lamps. Oxygen uptake, however, was lower under these conditions (Figures 2 and 4). Wear on the experimental ergometer was apparently a contributing cause to the the decreased oxygen cost of a given riding velocity as the experiment progressed (Section 5.4). Ergometer wear cannot, however, account for the difference in the oxygen cost of cycling under these different conditions, as the order in which subjects were exposed to the different environment/clothing conditions was randomized. This suggests that the oxygen cost of cycling without fans and lamps (Treatment 1) is actually lower than with fans (Treatment 2) or with both fans and lamps (Treatment 3). This difference is apparently due to some effect related to the forced air flow produced by the fans, as oxygen uptake for a given riding velocity was similar for the rides performed with the fans only and with both the fans and lamps. It has been speculated

previously that the fans stimulate a non shivering thermogenesis which increases oxygen consumption (Section 5.5). This suggests that standard bicycle ergometry in the laboratory without simulated wind underestimates the oxygen cost of a given equivalent cycling velocity on the road, especially for less well trained cyclists.

On the other hand, thermoregulation during bicycling under standard laboratory conditions (Treatment 1) is apparently more difficult than when cycling with simulated wind (Treatments 2 and 3). Although oxygen uptake and thus metabolic heat production were lower during rides without the fans or lamps than when riding with the fans only or with both the fans and lamps, heart rate continued to rise throughout exercise without the fans and was similar to or higher than when riding with the fans. Thermoregulatory responses when riding without the fans were unable to prevent a developing hyperthermia, as indicated by the failure of core temperature to reach steady state levels for the moderately trained cyclists and the rise in core temperature at the end of exercise after the temporary attainment of a steady state for the highly trained cyclists. This rise in core temperature occurred despite a greater sweating rate without the fans, suggesting that the increased evaporative cooling rate resulting from this augmented sweating did not compensate for the lack of cooling wind. Furthermore, an elevated sweating rate without the fans may have been a contributing factor to the greater cardiovascular strain

observed under these conditions (Section 5.8).

Riding 55 km at a steady submaximal workrate wearing cotton clothing under standard laboratory conditions (Treatment 1) resulted in higher skin temperature, greater weight loss, greater sweat retained in the clothes and possibly higher heart rate than under similar conditions but with fans producing an air flow rate approximately equal to that which would be experienced during cycling on the road at the same velocity (Treatments 2 and 3). The lack of significant differences in thermoregulatory responses when riding at 20°C in cotton clothing with fans only (Treatment 2) or with both fans and lamps (Treatment 3) suggests that the wind, not the sun, is the factor which makes laboratory cycling different from cycling on the road at the same ambient temperature (Table 10). Forced air flow rate greatly augments convective and evaporative cooling (Sections 5.6 and Appendix 2). Without the fans sweating efficiency was probably lower (i.e., more sweat was retained in the clothing and dripped rather than evaporated from the skin), resulting in a higher sweating rate for the same evaporative cooling rate. Also, sweating rate probably increased to help compensate for the lower convective cooling rate under these conditions. Minute ventilation and body and ambient temperatures were similar for rides performed with and without the fans. Thus, the amount of water lost through respiration would have been comparable in both conditions. Subjects did not consume solids or liquids, or empty their bladder or bowels during the

exercise session, so these exchanges cannot account for the difference in body weight lost. Respiratory quotient and, as mentioned previously, minute ventilation were not different for cycling with and without fans, so the change in body mass resulting from the greater molecular weight of expired carbon dioxide than inspired oxygen can not explain the difference in body weight between rides performed at these different environmental conditions. Therefore, the greater body weight loss observed without the fans must have resulted from a higher sweating rate under these conditions.

Skin temperature was higher without the fans, presumably because of decreased skin cooling in the relatively still air. The observed 4°C greater skin temperature would widen the skin/ambient temperature gradient, theoretically raising combined evaporative, convective and radiative heat loss rates by over 200 W compared with the theoretical value for these cooling rates under the the same conditions but with skin temperature 4°C cooler (Appendix 2). This additional 200 W represents an increase of 45% in the total theoretical heat loss, and may explain the lack of differences in delta core temperature between rides performed without the fans and those conducted under the same environment/clothing conditions but with the fans. Besides widening the skin/ambient temperature gradient, warm skin also facilitates heat loss by decreasing venomotor tone. This increases venous volume and thus increases venous transit time. Increased transit time increases the amount

of heat which can be unloaded from the blood as it passes through cutaneous blood vessels (Rowell, 1983).

Thus, it appears that under the conditions of the present study, warm skin is beneficial because it increases the rate of heat flow from the body to the environment. Warm skin may be detrimental under different conditions, however. As discussed elsewhere (Sections 1.1.3, 1.1.5 and 5.6) the increased cutaneous blood flow and venous volume produced by warming the skin at a given core temperature reduces venous return to the heart. This causes heart rate to rise to maintain cardiac output. Mean heart rate tended to be higher during rides at 20°C without the fans than with the fans at the same ambient temperature. During submaximal work, it may be a net advantage to have a warmer skin and greater cooling rate despite a higher heart rate. As the cardiovascular system is stressed toward its limits, though, (e.g., by higher relative workrates or pregressive dehydration at the same workrate), thermoregulatory and cardiovascular requirements will be more difficult to satisfy simultaneously. Under these conditions, a failing adaptation may occur sooner with warmer skin. In the present study subjects could apparently maintain cardiovascular and thermal balance because the involved systems were within their limits.

5.7. Differences in thermoregulatory responses when exercising at 30°C in the laboratory wearing different garments:

Most of the variables measured in the present study reflecting the degree of heat stress were not significantly different when cycling in the heat wearing cotton, lycra or wool clothing (Table 11). This finding is surprising in light of the very different physical properties of the various materials tested. Inspection of the time course of changes in heart rate and core temperature when cycling in the laboratory at 30°C with fans and lamps wearing these different garments (Figures 3 and 5) reveals trends which suggest that lycra is slightly superior to cotton and clearly superior to wool in facilitating thermoregulation under these conditions. Estimates for the amount of heat gained or lost by various routes under the conditions of the present study help explain these findings. Although the formulae used to apportion values to various sources of heat loss or gain have been empirically validated, several assumptions must be made to apply them to the conditions of the present study. These assumptions and details of the calculations are presented in Appendix 2.

The main forcing function increasing body heat storage was the rate of metabolic heat production, calculated to be about 1100 W. An additional 200 W were added in the four environment/clothing conditions in which subjects were exposed to movie lamps simulating solar radiation. Approximately 300 W of

metabolic heat were dissipated as mechanical work. The rates of radiant and respiratory heat loss were relatively small. Their estimated combined value ranged from 25 to 100 W for different clothing/environment conditions. These estimates indicate that the main avenues of heat loss under all environment/clothing conditions were convection and evaporation. Evaporative and convective heat loss may each be calculated as the product of a heat loss coefficient and the skin/ambient temperature difference. The coefficients of convective and evaporative heat loss each consist of a constant and an exponential function of air speed. Thus, evaporative and convective cooling are greatly enhanced at high air speeds and/or with a wide skin/ambient temperature gradient.

The estimated rate of body heat storage for riding in the laboratory wearing cotton clothing at 20°C with no fans or lamps yielded a predicted increase in core temperature of 1.5°C after 88 minutes of exercise, while the observed value of delta core temperature was 1.4°C. Observed delta core temperature was similar for the other environment/clothing conditions but there were large differences between these observed values and the relevant values predicted from heat balance calculations. The estimated value of approximately 500 W for convective cooling rate while cycling at 20°C with the fans seems too large. Convection can only remove heat from a surface actually exposed to the air. The equations for convective and evaporative cooling used in the present estimates were derived from studies of nude

men exposed to forced air flow. In clothed subjects, skin temperature will initially be higher than the temperature of the surface of the clothing. The skin/ambient temperature difference will overestimate the actual heat flow gradient, and thus convective cooling rate will be overestimated. Estimated convective cooling rate was considerably lower for rides at 30°C with the fans than at 20°C with the fans. This difference is expected because the skin/ambient gradient is narrower at the higher temperature.

Evaporative cooling rate appears to have been grossly overestimated for the rides at 20°C with the fans while wearing cotton clothing (Treatments 2 and 3). If convective cooling rate under these conditions was overestimated by about 40% (200 W), only about 300 W of evaporative cooling would have been required to account for the 1.4°C elevation in core temperature observed after 88 minutes of exercise for Treatment 2. The estimated 1500 W of evaporative cooling under these environment/clothing conditions assumed that the skin was completely wetted with sweat. Approximately 20% of the skin surface would need to be wet for a nude subject to achieve 300 W of evaporative cooling under these environmental conditions. The equation used to estimate evaporative cooling is appropriate for nude subjects at steady state sweating rate. Actual evaporative cooling rate in clothed subjects will be less than the value estimated by this equation until sweating rate stabilizes and the sweat has passed to the surface of the clothing. Even when the surface of the clothing

is wetted with sweat, the rate of evaporative cooling of a clothed subject is less than that of a nude subject producing the same amount of sweat, as the air provides some of the heat required to evaporate sweat from the clothes (Kerlake, 1972; Nagata, 1978). This error is expected to be greater with thicker materials such as wool because of the greater distance from the surface of the skin to the surface of the clothing. If actual evaporative cooling rate averaged over the whole period of exercise was only half of the estimated value per unit surface area of the skin wetted with sweat, then approximately 40% of the skin would need to be wet to balance the heat storage equation for cycling at 20°C wearing cotton clothing with fans but no lamps. Under the same conditions but with the lamps, evaporative cooling rate would need to be larger to offset the "solar" heat load. Pursuing this argument, 75% of the skin would need to be wetted with sweat to achieve an evaporative cooling rate of 500 W. Such a cooling rate would yield a net heat storage rate of 50 W, which would account for the observed 1.2°C increase in core temperature at the end of exercise.

The slower rise in rectal temperature when wearing cotton clothing at 20°C without fans or lamps compared to rides with the fans for the same temperature and clothing is probably the result of the lower relative metabolic rate ($\dot{V}O_2/\dot{V}O_{2\text{ max}}$) and associated lower rate of heat production in this condition. The more rapid rise in core temperature when cycling while wearing lycra compared with other clothing at 30°C with fans and lamps

may be related to the higher mean skin temperature observed while wearing the lycra. Lycra is less porous than cotton or wool, so will allow less air to reach the skin (Forbes, 1949). This decreases evaporative and convective cooling rates, which causes body heat storage rate to increase initially. When the lycra clothing has become wetted with sweat and heated to skin temperature, cooling rate is enhanced, body heat storage rate slows, and steady state core temperature is not different from wearing cotton or wool. The more rapid rise in heart rate with the onset of exercise at 30°C wearing lycra than other clothing may also be a result of the interaction between skin blood flow, venous return and heart rate. Skin temperature was warmer while wearing lycra than the other garments under these conditions. Warmer skin inhibits cutaneous vasoconstriction and venoconstriction, and may also have an active vasodilator effect (Rowell, 1983). This allows skin blood flow and skin venous volume to increase. The decreased venous return necessitates an increased heart rate to maintain cardiac output. The more rapid rise in heart rate during exercise at 20°C wearing cotton clothes with the lamps than without the lamps for the same temperature and clothing may similarly be due to the local heating effect of the lamps.

In the present study the rate of "solar" heat produced by the movie lamps was $678 \text{ W}\cdot\text{m}^{-2}$. This rate of radiant heating was selected to approximate the value of $1000 \text{ W}\cdot\text{m}^{-2}$ reported by Mitchell, J. W. (1977) as a typical solar heat load on a clear

day. This may have been an unrealistically large heat load. Pugh et al. (1967) calculated the solar heat load during a marathon run at only $64 \text{ W}\cdot\text{m}^{-2}$ for a summer day with 20-40% cloud cover. Adams et al. (1975) reported a similar value of $42 \text{ W}\cdot\text{m}^{-2}$ for the solar heat load during a marathon run.

The whole body, not just the core, acts as a heat sink. The previous discussion and the estimates in Appendix 2 have assumed for the sake of simplicity that core temperature reflects mean body temperature. A weighted average of peripheral (i.e., skin) and core temperatures may represent mean body temperature better. Also, the rate of change of core temperature was assumed to be linear, while Figures 2 to 5 show that it usually rose exponentially. Observed core temperature rose more quickly at the onset of exercise than predicted by a linear function, then rose more slowly than predicted as exercise continued.

The evaluation of the thermoregulatory consequences wearing different garments while exercising in the heat is greatly complicated by man's ability to accelerate the rate of heat loss by one route to compensate for impaired heat loss capacity of other avenues. A series of laboratory and field studies for the United States military (Forbes, 1949) failed to find any significant differences in the thermoregulatory responses of men walking in the heat with wind velocity varied from 0.1 to $3.1 \text{ m}\cdot\text{sec}^{-1}$ while wearing clothing with very different physical properties. The material expected by these researchers to have superior heat loss capability because of its greater

permeability actually had greater resistance to heat flux because of its greater thickness. However, increased skin temperature increased the skin/ambient temperature gradient and the cooling rate. The net result was that there was no difference in the thermal effects of the different garments. Man may also thermoregulate by varying regional heat loss rate during acclimatization to heat (Hoffler, 1968) and to compensate for increased resistance to heat flux at a portion of the body surface. Goldman (1981) evaluated the thermoregulatory responses of eight male volunteers wearing an outer garment impermeable to sweat while walking in a heated room. Core temperature was similar whether the material covered 25 or 50% of the body, apparently because evaporative cooling rate increased at the uncovered portion of the body in the latter condition. The capacity for such compensation is limited, as indicated by the larger increases in core temperature when more than 50% of the body was covered with the impermeable material.

5.8. Changes in oxygen uptake, core temperature, and heart rate during prolonged, steady-state exercise:

In the present study, heart rate, core temperature, and oxygen uptake increased progressively for the approximately 90 minutes of exercise (Figures 2 to 5 and Table 6). These results are apparently at least partially due to dehydration and the following mechanism may be proposed. Sweating reduced plasma

volume, which decreased venous return and resulted in a decreased stroke volume. Decreased plasma volume and sweat lying on the surface of the skin together inhibited sweating drive. The decreased sweating rate resulted in a decreased evaporative cooling rate, and thus core temperature rose.

The small ($0.09 \text{ litres} \cdot \text{min}^{-1}$) but significant increase in oxygen uptake as exercise progressed in the present study probably does not result from dehydration. Two possible explanations for this are that since metabolic rate is related to core temperature, every one degree C rise in core temperature will produce an increase in metabolic rate, currently estimated at a level of 13% (Astrand and Rodahl, 1977). Secondly, the oxygen cost of producing a given mechanical power output may increase as fatigue ensues. Muscular contraction may become more inefficient as fuel supplies in skeletal muscle are depleted. A complete explanation of the rise in oxygen uptake is complicated by the observation that this effect was only significant in two of the environment/clothing conditions. At 20°C wearing cotton clothing with fans but no lamps (Treatment 2) and at 30°C wearing wool clothing with both fans and lamps (Treatment 6), oxygen uptake increased significantly during all three specified exercise intervals. There were no significant differences in oxygen uptake between any time periods for any of the other environment/clothing conditions. It seems most reasonable to interpret the change in oxygen uptake during the exercise period in the present study as a consequence of a generalized increase

in metabolic rate concomittant with a rising core temperature, and a decreasing efficiency of muscular contraction accompanying the fatigued state. Mean core temperature at the end of an average of 88 minutes of continuous cycling at a mean $65\% \dot{V}O_2$ max ranged from 37.9°C to 38.5°C for the two groups of subjects and various environment/clothing conditions. These values are comparable to, but in the lower end of the reported range of 38°C to 40°C for core temperature under these condtions (Section 1.1.1).

5.9. Comparison of thermoregulatory responses when cycling in the laboratory with simulated wind and radiant heat load at hot and moderate ambient temperature:

In the present study thermoregulatory response during exercise was affected by ambient temperature. Exercise at 30°C with the fans and lamps and wearing cotton clothing was more stressful than during comparable conditions at 20°C as indicated by the higher heart rate and core temperature and the greater body weight loss due to sweating at the higher ambient temperature (Tables 10 and 11). The significant but low correlation ($r=0.25$) between relative metabolic rate ($\dot{V}O_2/\dot{V}O_2$ max) and steady state levels of core temperature suggests the importance of factors other than metabolic rate in accounting for the degree of elevation in core temperature during exercise. Thermoregulatory response was apparently determined both by the

heat produced as a byproduct of exercise and by the ability of the body to dissipate this heat under the prevailing environmental conditions. Radiant, evaporative and convective cooling rate depend on the temperature gradient between the skin and the surroundings, which is smaller at a higher ambient temperature. Nielsen's (1938, 1979) classical observation that core temperature is proportional to relative metabolic rate and independent of ambient temperature suggests that his subjects were able to compensate for the narrowed skin/ambient gradient at higher ambient temperatures by increasing the proportion of their body surface area which was wetted with sweat. Thus, although evaporative cooling rate per unit surface area of wetted skin may have been lower for Nielsen's subjects at higher ambient temperature, the total area available for evaporative heat loss may have increased. In the present study, exercise was more prolonged and water was withheld from subjects during exercise. Subjects did sweat more at 30°C than at 20°C and this probably helped them thermoregulate initially. As exercise progressed, however, this adaptation was apparently less effectual, perhaps because of competing thermoregulatory and cardiovascular demands (Section 5.7). Thus, thermoregulatory balance began to deteriorate earlier during exercise at 30°C than at 20°C because of the greater barrier to heat loss imposed by the hotter environment.

5.10. Hematocrit:

Hematocrit varies with the rate of red blood cell production, dehydration, etc., but it is unlikely that the observed variation in hematocrit (Table 13) may be explained by these factors alone. Rather, they may result from methodological problems. Blood samples were centrifuged soon after being drawn, then were read immediately. It is unlikely that evaporation, even at ambient temperatures of 30°C, would cause any appreciable hemoconcentration over this short a time period. Stroking the finger before pricking may have caused increased capillary hydrostatic pressure. This would force some plasma from the capillaries into the adjacent interstitial spaces. If some of this extracapillary plasma did not flow out through the lancet puncture, hematocrit would be falsely elevated. In addition, blood samples may not have been spun long enough to produce complete separation of red cells and plasma. When the consistently high hematocrit was noticed, a follow up test was conducted to determine the effect of increased centrifugation time on hematocrit reading. Hematocrit reading was about 1% packed cell volume (PCV) lower when centrifugation time was doubled to four minutes. Hematocrit lowered another 1% PCV following an additional two minutes of spinning. Further increase in centrifugation time did not produce any further measurable change in hematocrit. These results suggest that hematocrit in the first 52 trials may have been consistently

overestimated by about 2% PCV.

The negative hematocrit and plasma volume changes with exercise were in the expected direction. However, the magnitude of these changes was less than expected (Section 1.1.4). This may have been the result of stagnation of circulation in the fingers. During the approximately 90 minutes of continuous exercise in each laboratory trial, subjects rested their hands on the bicycle handlebars. This may have caused a reduced blood flow to the fingers. Thus, blood obtained from the fingertip may not have accurately represented the total circulation. The suggestion that the prolonged pressure on the hands may have impaired blood flow to the fingers is supported by observations and reports of subjects. Subjects occasionally removed one hand at a time from the handlebars to extend the fingers and shake the arm. Some subjects were observed to have pale fingertips at the end of exercise, and some subjects reported that their fingers felt numb and/or cold. Blood samples from the earlobe might have shown larger hematocrit changes with exercise. This technique had been considered for the present study, but was rejected because it was felt that this method, although potentially less painful, might make subjects more anxious. Hematocrit may be a useful index of plasma volume loss due to sweating during exercise in the heat, but the researcher should be aware of the potential methodological problems mentioned above.

5.11. Heat flux:

It was expected that voltage output from the heat flux transducers taped to the skin and pinned to the cycling clothing would reveal differences in the resistance to heat flow across the different garments. Average cycling velocity, and thus, mechanical power output, was similar for the different clothing/environment conditions. There is no reason to suspect that mechanical efficiency should have differed between treatments. Therefore, heat production should have been similar for the different treatments. During calibration, when the heat source was under the heat flux transducer the voltage output was positive, while a negative output was produced with the transducer inverted. Transducers were attached to the skin and clothing at the thigh and scapula. At 20°C with no fans or lamps (Treatment 1), and at 20°C with fans but without lamps (Treatment 2), the output from the transducers should have been positive. In other laboratory conditions in the present study (Treatments 3 to 6), movie lamps directed $678 \text{ W}\cdot\text{m}^{-2}$ of radiant energy at the subject's back. Metabolic heat production was estimated at $564 \text{ W}\cdot\text{m}^{-2}$ (Section 1.1.6). This metabolic heat could, theoretically, have been dissipated at the whole surface of the body. The surface area of the back is only a portion on the total body surface area. Therefore, it was expected that with the lamps radiant heat gain would exceed metabolic heat

loss at the back, and that the voltage output from the heat flux transducers pinned to the back of the clothing would have a negative sign. The expected sign of the voltage output from the transducer taped to the skin on the back was unclear. Certainly, the radiant energy from the lamps would eventually penetrate the clothing and reach the skin. This was expected to happen more rapidly for clothing which absorbed a greater proportion of the incident radiant energy and for clothing with a lower heat content (i.e., with lower capacity to store heat in the fibres of the clothing). The radiant heat reaching the skin would compete with the metabolic heat leaving the body, and the difference would, theoretically, determine the sign of the voltage output from the transducer on the skin of the back. Both transducers on the thigh were effectively shielded by the subject's trunk from the movie lamps. Thus, the output from these transducers should always have been positive. A greater difference in the output from these two transducers for a given treatment would imply a greater resistance of the clothing worn to heat flux; i.e., more heat was being trapped inside the clothing. This would cause skin temperature to rise. If skin temperature exceeded core temperature, another heat load would be added to the body.

The mean value of heat flux measured at the skin and over the clothing on the thigh had a negative sign for almost all of the treatments. This was opposite to the expected result. The heat flux transducers were marked on one side. The experimenter

was careful to attach the heat flux transducers to the subject such that the marked side was visible. Therefore, a simple inversion of the transducer does not appear to be a plausible explanation for the anomalous results. Body core and skin temperature always exceeded ambient temperature. The thighs were shielded from radiant energy. Metabolic heat production was substantial and most of this heat must have been dissipated from the body, or core temperature would have increased to unrealistically high levels. It seems impossible under the conditions of the present study for net heat flow at the thigh to be toward the body. Therefore, it is most likely that the heat flux transducers were not functioning properly and thus these data have not been presented or discussed.

5.12. Comparison of actual road cycling with simulated road riding in the laboratory:

Laboratory simulated road riding and actual cycling on the road probably differ in other ways than their differing thermoregulatory demands (Table 13). As discussed previously (Section 2.4), in the laboratory subjects must cycle in a more constrained posture. Subjects were permitted to pedal while standing, but the mechanics of this maneuver seem different in the laboratory, and it provides less relief than on the road. Consequently, muscle energy stores may be depleted more rapidly at the same external work rate during laboratory cycling. Also,

motivation is probably enhanced and boredom minimized during actual road cycling because of the companionship and competition with other riders, the greater sensory stimulation, and the heightened arousal required to avoid obstacles. Furthermore, in most road cycling (except perhaps solo time trials and to a lesser extent team time trials) the workrate varies considerably due to changes in terrain and due to periodic bursts of speed by which cyclists attempt to lose their competitors. Finally, when a group of cyclists rides closely together, they can travel considerably faster than the individuals could by themselves. On the road, a group of cyclists could probably ride at $37 \text{ km}\cdot\text{h}^{-1}$ at a relative workrate below that required to achieve the same equivalent velocity in the laboratory. In the present study, wear on the experimental ergometer apparently lowered the oxygen cost of a given cycling velocity. Thus, the physiological and thermoregulatory responses observed in the present laboratory studies are probably representative of cycling on the road at $37 \text{ km}\cdot\text{h}^{-1}$ in a group. The demands of solo riding on the road at the same velocity should be greater.

6.0. Conclusions and directions for future research:

6.1. Experimental ergometer:

The Racer Mate Wind Load Simulator is a viable form of bicycle ergometer exercise. The oxygen cost of various workrates is similar to actual cycling on the road at the same velocity. The cyclist uses his/her own bicycle, thus, the muscle groups used in cycling are more specifically challenged. The subject is more comfortable, and probably more efficient, than on conventional bicycle ergometers. Consequently, subjects can probably exercise for a longer duration and achieve a higher maximal power output. Subjects may also be able to attain higher maximal rates of oxygen uptake using the Racer Mate than using standard ergometers.

The Racer Mate stand and impeller apparatus must be adjusted for each subject's bicycle. Initially, this process is time-consuming, but with practice these adjustments can be made in a few minutes. Workrates on the Racer Mate are a function of gear ratio and pedalling frequency. A constant workrate depends on maintenance of a constant pedalling frequency. The Pacer 2000 bicycle computer used in the present study provides visual feedback which helps the subject pedal at a steady rate, and allows the experimenter to measure pedalling frequency, average

velocity, total distance travelled, time and heart rate.

The Racer Mate's aluminum roller may wear out, which may cause a substantial decrease in the energy demand of a given cycling velocity. A roller manufactured from a harder material (i.e., stainless steel) might minimize this problem. With respect to the above, laboratory studies using trained cyclists as subjects should consider using a Racer Mate type ergometer rather than a conventional bicycle ergometer.

6.2. Relative metabolic rate during cycling:

Trained cyclists are capable of exercising at 65% $\dot{V}O_2$ max for at least 90 minutes continuously in the laboratory or on the road. Higher workrates may be sustained for this duration, but may not be typical of most bicycle racing or training. Depletion of muscle energy stores may be an important factor limiting the intensity and duration of prolonged submaximal bicycle exercise.

6.3. Sweating rate:

Sweating rate is substantial during actual road riding and simulated road riding in the laboratory. At 65% $\dot{V}O_2$ max (37.3 km \cdot h⁻¹, or an estimated 268 W for the subjects in the present study), sweating rates of 0.99 and 1.33 litres \cdot h⁻¹ were recorded at ambient temperatures of 20^o and 30^oC, respectively. These sweating rates resulted in average body weight losses of 1.8 and

2.7% of initial weight. Unless cyclists replace this fluid during exercise, their exercise performance and ultimately their health may be compromised. At the workrates used in the present study, a 70 kg cyclist would theoretically lose 2% of his body weight due to sweating in about 60 minutes at 30°C, or 90 minutes at 20°C. To maintain optimal exercise capacity after this time period, cyclists should consume fluid in amounts roughly equal to their sweating rate. Thirst is not a reliable indicator of the extent of dehydration.

6.4. Thermoregulatory responses during cycling when wearing different clothing:

Under the conditions of the present study there were no real differences in thermoregulatory responses to prolonged simulated road cycling in the heat wearing clothing made of cotton, lycra or wool. This is surprising in view of the very different physical properties of these different materials. This suggests that different but equally effective mechanisms are used to regulate body temperature when exercising in the heat in these different garments. The overwhelming cooling effect of the wind at typical cycling velocities may mask any differences in the thermal properties of the different fabrics tested in this study. Thermoregulation should probably not be a major consideration in the selection of cycling clothing on dry days at ambient temperatures between 20°C and 30°C.

6.5. Changes in heart rate, core temperature, and oxygen uptake during prolonged submaximal bicycling:

During prolonged bicycling at relatively constant velocity, heart rate and core temperature changed progressively, which has been explained as a consequence of dehydration. This result has serious implications for the use of heart rate to infer oxygen uptake during prolonged submaximal bicycle exercise. Heart rate for a given relative metabolic rate ($\dot{V}O_2 / \dot{V}O_{2 \text{ max}}$) will increase as exercise continues if subjects are not adequately rehydrated, and relative metabolic rate will be overestimated. Oxygen uptake also increased slightly, but significantly, as exercise progressed. This may be due to increased metabolic activity at higher body temperature and/or to decreased efficiency with fatigue. The suggestion that dehydration causes rising core temperature and heart rate has been tested by other investigators by requiring subjects to replace fluid lost as sweat by drinking water during exercise. A similar design could be used to study this effect under the conditions of the present study.

6.6. Laboratory ergometry compared to simulated road cycling:

Thermoregulatory responses to bicycling in the laboratory at an ambient temperature of 20°C are different from simulated road cycling at the same temperature. Without the wind, sweat rate was greater, the clothing was soaked with sweat, skin temperature was higher, and there was a trend toward higher heart rate. Failure to account for the tremendous cooling effect of the wind in laboratory studies of cyclists performing extended submaximal exercise may result in an overestimation of the physical demands of actual road cycling.

REFERENCES

- Adams, W.C., R.H. Fox, A.J. Fry, and I.C. MacDonald. Thermoregulation during marathon running in cool, moderate, and hot environments. J. Appl. Physiol. 38:1030-1037, 1975.
- Adolph, E.F. and Associates. Physiology of Man in the Desert. New York: Interscience Publishers, Inc., 1947.
- Aikas, E., M.J. Karvonen, P. Piironen, and R. Ruosteenoja. Intramuscular, rectal and oesophagal temperature during exercise. Acta Physiol. Scand. 54:366, 1962.
- Asmussen, E. and M. Nielsen. The regulation of the body temperature during work performed with the arms and with the legs. Acta Physiol. Scand. 14:373-382, 1947.
- Astrand, P.O. and K. Rodahl. Textbook of Work Physiology. New York: McGraw-Hill, 1977.
- Astrand, P.O. and B. Saltin. Plasma and red cell volume after prolonged severe exercise. J. Appl. Physiol. Vol. 19(5):829-832, 1964.
- Bergh, U., and B. Ekblom. Physical performance and peak aerobic power at different body temperatures. J. Appl. Physiol. 46:885-889, 1979.
- Bernheim, J., and J.N. Cox. Coup de chaleur et intoxication amphetamine chez un sportif. Schweizerische Medizinische Wochenschrift. 90:322-331, 1960.
- Brengelman, G.L. Circulatory adjustments to exercise and heat stress. Annual Review of Physiology. 45:191-212, 1983.
- Brooke, J.D., and G.J. Davies. Comment on "Estimation of the energy expenditure of sporting cyclists." Ergonomics, 16:237-238, 1973.
- Burke, E. Causes of fatigue in competitive road cycling. Sports Coach, 3:20-22, 1979.
- Burke, E. Physiological characteristics of competitive cyclists. Physician and Sportsmedicine, 8:79-84, 1980a.
- Canadian Cycling Association. Racing Rules. Ottawa, Canada, 1982.
- Candas, B., J.P. Libert, and J.J. Vogt. Human skin wettedness and evaporative efficiency of sweating. J. Appl. Physiol. 46:522-528, 1979.

- Cannon, B., J. Nedergard, and U. Sundin. Thermogenesis, brown fat and thermogenin. In Musacchia, X.J., and L. Jansky (Eds), Survival in the Cold, pp. 99-120, New York: Elsevier/North Holland, 1981.
- Carlile, F. Effects of preliminary passive warming up on swimming performance. Res. Q. 27:143-151, 1956.
- Carpenter, T.M. Tables, Factors and Formulas for Computing Respiratory Exchange and Biological Transformations of Energy. Publication 303C, Washington, D.C.: Carnegie Institute of Washington, 1948.
- Cerreteli, P. and P.E. DiPrampo. Kinetics of respiratory gas exchange and cardiac output at the onset of exercise. Scand. J. Resp. Dis., S77:A35, 1971.
- Conover, W.J. Practical Nonparametric Tests. New York: John Wiley and Sons, Inc., 1971.
- Costill, D.L., L. Branam, D. Eddy, and W. Fink. Alterations in red cell volume following exercise and dehydration. J. Appl. Physiol. 37:912-916, 1974.
- Costill, D.L., W.F. Kramer, and A. Fisher. Fluid ingestion during distance running. Arch. Environ. Health. 21:520-525, 1970.
- Costill, D.L., and K.E. Sparks. Rapid fluid replacement following thermal dehydration. J. Appl. Physiol. 34:299-303, 1973.
- Davies, C.T.M. Influence of air flow and skin temperature at the onset, during and following exercise. Ergonomics. 23:559-569, 1980.
- Donhoffer, Sz. Non-shivering thermogenesis: Past and present. In Jansky, L. (Ed), Nonshivering Thermogenesis, Lisse, The Netherlands: Sweta and Zeitlinger N.V., 1971.
- Ekblom, B., C.J. Greenleaf, J.E. Greenleaf, and L. Hermansen. Temperature regulation during exercise dehydration in man. Acta Physiol. Scand. 79:475-483, 1970.
- Firth, M.S. A sport-specific training and testing device for racing cyclists. Ergonomics. 24:565-571, 1981.
- Forbes, W.H. Laboratory and field studies. In Newburgh, L.H. (Ed), Physiology of Heat Regulation and the Science of Clothing, pp. 320-388, Philadelphia: Saunders, 1949.
- Fortney, S.M., E.R. Nadel, C.B. Wenger, and J.R. Bove. Effect of blood volume on sweating rate and body fluids in exercising humans. J. Appl. Physiol. 51:1594-1600, 1981a.
- Fortney, S.M., E.R. Nadel, C.B. Wenger, and J.R. Bove. Effect of acute alterations of blood volume on circulatory performance in humans. J. Appl. Physiol. 50:292-298, 1981b.

- Foster, C., and J.T. Daniels. Aerobic power of competitive cyclists. Australian J. of Sports Medicine, 7:111-112, 1975.
- Genovely, H., and Stamford, B.A. Effects of prolonged warm-up exercise above and below anaerobic threshold on maximal performance. Eur. J. Appl. Physiol. 48:323-330, 1982.
- Gisolfi, C.V., and J.R. Copping. Thermal effects of prolonged treadmill exercise in the heat. Med. Sci. Sport. 6:108, 1974.
- Givoni, B. and R.F. Goldman. Predicting rectal temperature response to work, environment and clothing. J. Appl. Physiol., 32:812-822, 1972.
- Givoni, B. and R.F. Goldman. Predicting heart rate response to work, environment and clothing. J. Appl. Physiol., 34:201-204, 1973.
- Goldman, R.F. Evaluating the effects of clothing on the wearer. In Cena, K. and J.A. Clark (Eds), Bioengineering, thermal physiology and comfort, pp. 41-55, New York: Elsevier/North Holland, 1981.
- Greenleaf, J.E. Hyperthermia and exercise. In Robershaw, D. (Ed.), International Review of Physiology. 20:157-208, 1979.
- Greenleaf, J.E., and B.L. Castle. Exercise temperature regulation in man during hypohydration and hyperhydration. J. Appl. Physiol. 30:847-853, 1971.
- Greenleaf, J.E., V.A. Convertino, and G.R. Mangseth. Plasma volume during stress in man: osmolality and red cell volume. J. Appl. Physiol. 47:1031-1038, 1979.
- Hanson, P.G. Heat injury in runners. Physician and Sportsmedicine. 7:91-96, 1979.
- Harrison, M.H., R.J. Edwards and D.R. Leitch. Effect of exercise and thermal stress on plasma volume. J. Appl. Physiol., 39:925, 1975.
- Hermansen, L., E. Hultman, and B. Saltin. Muscle glycogen during prolonged severe exercise. Acta Physiol. Scand. 71:129-131, 1967.
- Hofler, W. Changes in regional distribution of sweating during acclimatization to heat. J. Appl. Physiol. 25:503-506, 1968.
- Hultman, E. Studies on muscle metabolism of glycogen and active phosphate in man with special reference to exercise and diet. Scand. J. Clin. Lab. Invest., 19. Suppl. 94, 1967.
- Inger, F., and B. Stromme. Effects of active and passive warmup on the physiological response to heavy exercise. Eur. J. Appl. Physiol. 40:273-282, 1979.

- Johnson, J.M., and M.K. Park. Reflex control of skin blood flow by skin temperature: role of core temperature. J. Appl. Physiol. 47:1188-1193, 1979.
- Johnson, J.M., and M.K. Park. Effect of heat stress on cutaneous vascular responses to the initiation of exercise. J. Appl. Physiol. 53:744-749, 1982.
- Johnson, J.M., L.B. Rowell, and G.L. Brengelmann. Modification of the skin blood flow-body temperature relationship by upright exercise. J. Appl. Physiol. 37:880-886, 1974.
- Jurbala, P. A sport-specific test of aerobic power for competitive cyclists. Submission to Sport Canada, 1982.
- Kerslake, D. McK. The Stress of Hot Environments. Cambridge, England: University Press, 1972.
- Knochel, J.P. Environmental Heat Illness: An Eclectic Review. Archives of Internal Medicine. 133:841-864, May, 1974.
- Kozlowski, S. and B. Saltin. Effect of sweat loss on body fluids. J. Appl. Physiol. 19:1119-1124, 1964.
- Kyle, C.R. Reduction of wind resistance and power output of racing cyclists and runners travelling in groups. Ergonomics. 22:387-397, 1979.
- Kyle, C.R., and J. Mastropaolo. Reduction of wind resistance and power output of racing bicyclists and runners travelling in groups (abstract). Med. Sci. Sport. 8:56-57, 1976.
- Langford, M. Advanced Photography. London: The Focal Press, 1969.
- Legge, B.J. The Prediction of Maximal Aerobic Capacity for Trained and Untrained Males from Measurements made during Submaximal Bicycle Ergometry. M.Sc. Thesis, Simon Fraser University: Burnaby, B.C., Canada, 1983.
- Lehninger, A.L. Biochemistry. New York: Worth Publishers, Inc., 1975.
- Lollgen, H., T. Graham, and G. Sjogaard. Muscle metabolites, force and perceived exertion bicycling at varying pedal rates. Med. Sci. Sport Exer., 12(5):345-351, 1980.
- MacDougall, J.D., W.G. Reddan, C.R. Layton, and J.A. Dempsey. Effects of metabolic hyperthermia on performance during heavy prolonged exercise. J. Appl. Physiol. 36:538-544, 1974.
- Martin, J., S. Robinson, L. Wiegman, and H. Aulick. Effect of warmup on metabolic responses to strenuous exercise. Med. Sci. Sport. 7:146-149, 1975.
- Mitchell, D., C.H. Wyndham, A.J. Vermeulen, T. Hodgson, A.R. Atkins, and H.S. Hofmeyr. Radiant and convective heat transfer of nude men in dry air. J. Appl. Physiol. 26:111-118, 1969.

- Mitchell, J.W. Energy exchanges during exercise. In Nadel, E.R. (Ed.), Problems with Temperature Regulation During Exercise. New York: Academic Press, 1977.
- Mitchell, J.W., E.R. Nadel, and J.A.J. Stolwijk. Respiratory weight losses during exercise. J. Appl. Physiol. 32:474-476, 1972.
- Myhre, L.G., G.H. Hartung, and D.M. Tucker. Plasma volume and blood metabolites in middle-aged runners during a warm-weather marathon. Eur. J. Appl. Physiol. 48:227-240, 1982.
- Nadel, E.R. Circulatory and thermal regulation during exercise. Federation Proceedings, Federation of American Societies for Experimental Biology. 39:1491-1497, 1980.
- Nadel, E.R., R.W. Bullard, and J.A.J. Stolwijk. The importance of skin temperature in the regulation of sweating. J. Appl. Physiol. 31:80-87, 1971.
- Nadel, E.R., S.M. Fortney, and C.B. Wenger. Effect of hydration state on circulatory and thermal regulations. J. Appl. Physiol. 49:715-721, 1980.
- Nadel, E.R., and S.M. Horvath. A brief summary. In Nadel, E.R. (Ed.), Problems with Temperatures Regulation during Exercise. New York: Academic Press, 1977.
- Nadel, E.R. and J.A.J. Stolwijk. Effect of skin wettedness on sweat gland response. J. Appl. Physiol. 35:689-694, 1973.
- Nagata, H. Evaporative heat loss and clothing. J. of Human Ergology, (Tokyo). 7:169-175, 1978.
- Newby, J.C. Mathematics for the Biological Sciences, p. 52, Oxford: Clarendon Press, 1980.
- Nichols, M. A Comparison of Treadmill and Bicycle Ergometer Maximal Oxygen Uptake Values as Elicited by Competitive Cyclists. Master's thesis, Vancouver, Canada: University of British Columbia, 1977.
- Nielsen, B. Regulation of body temperature and heat dissipation at different levels of energy and heat production in man. Acta Physiol. Scand. 68:215-227, 1966.
- Nielsen, B. Thermoregulation in rest and exercise. Acta Physiologica Scandinavica Supplementum. 323:1-74, 1969.
- Nielsen, B., and M. Nielsen, Body temperature during work at different environmental temperatures. Acta Physiol. Scand. 56:120-129, 1962.
- Nielsen, B. Thermoregulation in rest and exercise. Acta Physiol. Scand. Suppl. 323:1-74, 1969.
- Nielsen, M. Die Regulation der Korpertemperatur bei Muskularbeit. Skand. Arch. Physiol. 79:193-230, 1938.

- Nielsen, M. Heat production and body temperature during rest and work. in Hardy, J.D., A.P. Gagge, and J.A.J. Stolwijk (Eds.) Physiological and Behavioral Temperature Regulation. Springfield, Illinois: Charles C. Thomas, 1979.
- Nishi, Y., and A.P. Gagge. Direct evaluation of convective heat transfer coefficient by naphthalene sublimation. J. Appl. Physiol. 29:830-838, 1970.
- Nonweiler, T. Air resistance of racing cyclists. Report No. 106, Cranfield, England: The College of Aeronautics, 1956.
- Osness, W.H. Changes in plasma during varied exercise conditions and its effect on plasma metabolite concentrations. Proceedings of Annual Meeting of the National College Physical Education Association for Men. 1968, pp 77-5.
- Perez, H.R. The effects of competitive road-racing on the body composition, pulmonary function, and cardiovascular system of sport cyclists. J. of Sports Medicine, 21:165-171, 1981.
- Piehl, K. Glycogen storage and depletion in human skeletal muscle. Acta Physiol. Scand. Suppl. 402, 1974. pp. 15-18.
- Pierau, F.K. and R.D. Wurster. Primary afferent input from cutaneous thermoreceptors. Federation Proceedings, 40(1):2819-2823, 1981.
- Pitts, G.C., R.E. Johnson, and R.C. Consolazio. Work in the heat as affected by intake of water, salt and glucose. Am. J. Physiol. 142:253-259, 1944.
- Pugh, L.G. Relation of oxygen intake and speed in competition cycling and comparative observations on the bicycle ergometer. Journal of Physiology, 241:795-808, 1974.
- Pugh, L.G. Air resistance in sport. In Jokl E. (Ed.) Advances in Exercise Physiology. Basel, Switzerland: Karger, 1976. pp. 149-164.
- Pugh, L.G.C.E., J.L. Corbett, and R.H. Johnson. Rectal temperatures, weight losses and sweat rates in marathon running. J. Appl. Physiol. 23:347-352, 1967.
- Ramanathan, N.C. A new weighting system for mean surface temperature of the human body. J. Appl. Physiol. 19:531-533, 1964.
- Roberts, M.F. and C.B. Wenger. Control of skin circulation during exercise and heat stress. Medicine and Science in Sports. 11:36-41, 1979.
- Roberts, M.F. and C.B. Wenger. Control of skin blood flow during exercise by thermal reflexes and baroreflexes. J. Appl. Physiol. 48:717-723, 1980.
- Robinson, S. and A.H. Robinson. Chemical composition of sweat. Physiol. Rev., 34:202-220, 1954.

- Rothwell, N.J., and M.J. Stock. A role for brown adipose tissue in diet-induced thermogenesis. Nature, 281:31-35, 1979.
- Rowell, L.B. Human cardiovascular adjustments to exercise and thermal stress. Physiological Reviews. 54:75-159, 1974.
- Rowell, L.B. Competition between skin and muscle for blood flow during exercise. In Nadel, E.R. (Ed.), Problems with Temperature Regulation During Exercise. New York: Academic Press, 1977.
- Rowell, L.B. Cardiovascular aspects of human thermoregulation. Circulation Research. 52:367-369, 1983.
- Rowell, L.B., G.L. Brengelmann, J.M.R. Detry and C. Wyss. Venomotor responses to rapid changes in skin temperature in exercising men. Journal of Applied Physiology. 30:64-71, 1971.
- Saltin, B. Circulatory response to submaximal and maximal exercise after thermal dehydration. J. Appl. Physiol. 19:1125-1132, 1964a.
- Saltin, B. Aerobic work capacity and circulation at exercise in man. Acta Physiol. Scand. Suppl. 230:1-52, 1964b.
- Saltin, B. Circulatory adjustments and body temperature regulation during exercise. In Hardy, J.D., A.P. Gagge and J.A.J. Stolwijk (Eds.) Physiological and Behavioral Temperature Regulation. Springfield, Illinois: Charles C. Thomas, 1979, pp. 316-323.
- Saltin B. and L. Hermansen. Esophageal, rectal and muscle temperature during exercise. J. Appl. Physiol. 21:1757-1762, 1966.
- Saltin B. and J. Stenberg. Circulatory response to prolonged severe exercise. J. Appl. Physiol. 19:833-836, 1964c.
- Sawka, M.N., R.G. Knowlton, and J.B. Critz. Thermal and circulatory responses to repeated bouts of prolonged running. Med. Sci. Sport. 11:177-180, 1979.
- Shibolet, S., M.C. Lancaster, and Y. Danon. Heat Stroke: A review. Aviation, Space and Environ. Med. 47:280-301, 1976.
- Siple, P.A. Clothing and climate. In Newburgh, L.H. (Ed), Physiology of Heat Regulation and the Science of Clothing, pp. 389-442, Philadelphia: Saunders, 1949.
- Steel, R.G.D. and J.H. Torrie. Principles and Procedures of Statistics: A Biometrical Approach. 2nd Edition. New York, New York: McGraw-Hill Book Company, 1980.

- Stolwijk, J.A.J., M.F. Roberts, C.B. Wenger, and E.R. Nadel. Changes in thermoregulatory and cardiovascular function with heat acclimation. In Nadel, E.R. (Ed.), Problems with Temperature Regulation During Exercise. New York: Academic Press, 1977.
- Strydom, N.B., and L.D. Holdsworth. The effects of different levels of water deficit on physiological responses during heat stress. Int. Z. angew. Physiol. 26:95-102, 1968.
- Swan, H. Neuroendocrine aspects of hibernation. In Muscchia, X.J., and L. Jansky (Eds), Survival in the Cold, pp. 121-138, New York: Elsevier/North-Holland, 1981.
- van Beaumont, W. Evaluation of hemoconcentration from hematocrit measurements. J. Appl. Physiol. 32:712-713, 1972.
- van Beaumont, W. J.E. Greenleaf, and L. Juhos. Disproportional changes in hematocrit, plasma volume, and proteins during exercise and bad rest. J. Appl. Physiol. 33:56-61, 1972.
- van Beaumont, W., J.C. Strand, J.S. Petrofsky, S.G. Hipskind, and J.E. Greenleaf. Changes in total plasma content of electrolytes and proteins with maximal exercise. Journal of Applied Physiology. 34:102-106, 1973.
- Vrijens, J., J.L. Pannier, and J. Bouckaert. Physiological profile of competitive road cyclists. J. Sports Medicine, 22:207-216, 1982.
- Weast, R.C. (Ed.) Handbook of Chemistry and Physics, 56th Edition. The Chemical Rubber Company: Cleveland, Ohio, 1975.
- Wells, C.L. Responses of physically active and acclimatized men and women to exercise in a desert environment. Med. Sci. Sports Exercise. 12:9-13, 1980.
- Wenger, C.B. and M.F. Roberts. Control of forearm venous volume during exercise and body heating. J. Applied Physiology. 48:114-119, 1980.
- Whipp, B.J. and K. Wasserman. Oxygen uptake kinetics for various intensities of constant-load work. J. Appl. Physiol., 33(3):351, 1972.
- White, J.A., G. Quinn, M. Al-Dawalbi and J. Mulhall. Seasonal changes in cyclists' performance: Part II. The British Olympic road race squad. British J. of Sports Medicine, 16:4-12, 1982.
- Whitt, F.R. Note on the estimation of the energy expenditures of sporting cyclists. Ergonomics. 14:419-424, 1971.
- Wissler, E.H., and R.B. Ketch. Errors involved in using thermal flux transducers under various conditions. Undersea Biomed. Res., 9(3):213-231, 1982.

- Wyndham, C.H. and N.B. Strydom. The danger of an inadequate water intake during marathon running. S. Afr. Med. J. 43:893-896, 1969.
- Wyndham, C.H. The physiology of exercise under heat stress. Annual Review of Physiology. 35:193-220, 1973.
- Wyndham, H., J. Morrison, C.G. Williams, N.B. Strydom, M.J.E. von Rahden, L.D. Holdsworth, C.H. Van Graan, A.J. Rensburg, and A. Joffe. Inter- and intra-individual differences in energy expenditure and mechanical efficiency. Ergonomics. 9:17-29, 1966.
- Yaglou, C.P. Thermometry in Physiology of Heat Regulation and the Science of Clothing. Newburgh, L.H. (Ed.) New York: Hafner Publishing Company, 1968.
- Zacks, R.M. Mechanical efficiencies of running and bicycling against a horizontal impeding force. Int. Z. angew Physiol. 31:249-258, 1973.

APPENDIX 1

Units	Abbreviation	Conversion
meters/second	$m \cdot s^{-1}$	$1 m \cdot s^{-1} = 2.237 \text{ miles} \cdot h^{-1}$
kilometer/hour	$km \cdot h^{-1}$	$1 km \cdot h^{-1} = 0.621 \text{ miles} \cdot h^{-1}$
litres/minute	$l \cdot \text{min}^{-1}$	$1 l = 1.057 \text{ U.S. qt.}$
beats/minute	$\text{beats} \cdot \text{min}^{-1}$	
grams	g	$1 g = .001 \text{ kg}$
kilograms	kg	$1 \text{ kg} = 2.205 \text{ pounds}$
centimeters	cm	$1 \text{ cm} = 0.394 \text{ inches}$
millimeters	mm	$1 \text{ mm} = 0.1 \text{ cm}$
degrees C	$^{\circ}\text{C}$	$^{\circ}\text{C} = (^{\circ}\text{F} - 32) 5/9$
kiloPascals	kPa	$1 \text{ kPa} = 7.526 \text{ mm Hg}$
Joules	J	$1 \text{ J} = 1 \text{ Nm}$ $= 2.389 \cdot 10^{-4} \text{ kcal}$ $= 0.102 \text{ kpm}$
Watts	W	$1 \text{ W} = 1 \text{ J} \cdot \text{s}^{-1}$ $= 1.341 \cdot 10^{-3} \text{ hp}$ $= 1.433 \cdot 10^{-2} \text{ kcal} \cdot \text{min}^{-1}$ $= 6.12 \text{ kpm} \cdot \text{min}^{-1}$

APPENDIX 2

Estimation of the rates of heat gain and loss by various routes during 55 km (88 minutes) of steady state submaximal cycling in the laboratory under different environment/clothing conditions.

Body surface area (BSA) for mean height of 178 cm, mean weight of 71.7 kg = 1.9 m^2 (Kerslake, 1972 after DuBois)

Mechanical power output, W:

$$\text{Mean cycling speed} = 37.3 \text{ km}\cdot\text{h}^{-1}$$

$$W = 0.019 \cdot V^{2.64} \text{ Watts}$$

(Firth, 1981)

$$\text{where } V = \text{velocity in } \text{m}\cdot\text{s}^{-1}$$

$$= 268 \text{ W}$$

$$= 268/1.9 = 141 \text{ W}\cdot\text{m}^{-2}$$

Metabolic heat production, M:

Mechanical efficiency of cycling = 25%
(Wyndham et al., 1966; Whitt, 1971; Zacks, 1973)

$$M = 268/.25 = 1072 \text{ W}$$

$$= 1072/1.9 = 564 \text{ W}\cdot\text{m}^{-2}$$

Convection, C:

$$C = hc (Ts - Ta) \text{ W}\cdot\text{m}^{-2} \quad (\text{Kerlake, 1972})$$

where hc = the convective heat exchange coefficient
($\text{W}\cdot\text{m}^{-2}/^{\circ}\text{C}$)

Ts = skin temperature ($^{\circ}\text{C}$)

Ta = air temperature ($^{\circ}\text{C}$)

with wind, $hc = 8.3 V$ (Kerlake, 1972)

where V = air speed ($\text{m}\cdot\text{s}^{-1}$)

without wind, $hc = 8.3$ (Nishi and Gagge, 1970)

Present study:

Condition	V	hc	Ts	Ta	C ($\text{W}\cdot\text{m}^{-2}$)
1	n/a	8.3	34.3	20.0	119
2	10.7	27.2	30.4	20.0	283
3	10.7	27.2	29.6	20.0	261
4	10.7	27.2	32.1	30.0	57
5	10.7	27.2	32.9	30.0	79
6	10.7	27.2	32.3	30.0	63

Convection (continued):

Calculating hc for forced convection (i.e., with wind) from formula described by other authors gives similar values.

$$hc = v^{0.6} \quad (\text{kcal} \cdot \text{h}^{-1} \cdot \text{C}^{-1})$$

(Nelson et al., 1947)

for surface area of 1.8 m^2
where $v = \text{air speed (m} \cdot \text{min}^{-1}\text{)}$

$$1 \text{ kcal} \cdot \text{h}^{-1} = 1/60 \text{ kcal} \cdot \text{min}^{-1}$$

$$1 \text{ kcal} \cdot \text{min}^{-1} = 69.767 \text{ W}$$

$$hc = (69.767/60) (1/1.8) v^{0.6} \text{ W} \cdot \text{m}^{-2} \cdot \text{C}^{-1}$$

In the present study, $v = 10.7 \text{ m} \cdot \text{s}^{-1}$
 $= 642 \text{ m} \cdot \text{min}^{-1}$

$$hc = 0.64 \cdot 642^{0.6} = 30.7 \text{ W} \cdot \text{m}^{-2} \cdot \text{C}^{-1}$$

Alternatively,

$$hc = 7.25 v^{0.6} \text{ W} \cdot \text{m}^{-2} \cdot \text{C}^{-1} \quad (\text{Mitchell, D. et al., 1969})$$

or

$$hc = 8.6 v^{0.531} \text{ W} \cdot \text{m}^{-2} \cdot \text{C}^{-1} \quad (\text{Mitchell, J.W., 1977})$$

where $v = \text{air speed (m} \cdot \text{s}^{-1}\text{)}$

In the present study, these last two equations for hc give values of 30.1 and 30.3 $\text{W} \cdot \text{m}^{-2} \cdot \text{C}^{-1}$ respectively.

Evaporation, E:

$$E = h_e (P_s - P_a) W \cdot m^{-2} \quad (\text{Kerlake, 1972})$$

where h_e = evaporation coefficient
($W \cdot m^{-2} / kPa$)

$$= 124 V$$

where V = air speed ($m \cdot s^{-1}$)

P_s = vapor pressure of water at skin temperature (kPa)

P_a = vapour pressure of water at ambient temperature (kPa)

Present study

Condi- tion	V	h_e	T_s	P_s		T_a	P_a		E ($W \cdot m^{-2}$)
				mmHg	kPa		mmHg	kPa	
1	0.2	55	34.3	40.5	5.41	20.0	17.5	2.34	169
2	10.7	406	30.4	32.6	4.34	20.0	17.5	2.34	812
3	10.7	406	29.6	31.1	4.14	20.0	17.5	2.34	731
4	10.7	406	32.1	35.9	4.78	30.0	31.8	4.24	219
5	10.7	406	32.9	37.5	5.00	30.0	31.8	4.24	309
6	10.7	406	32.3	36.3	4.84	30.0	31.8	4.24	244

Values for vapour pressures obtained from Carpenter, 1948; Kerlake, 1972; Weast, 1975.

Evaporation (continued):

Similar values for E can be estimated from the formula reported by Mitchell, J.W. (1977):

$$E = 2.2 hc (Ps - Pa) W \cdot m^{-2}$$

where hc = convective coefficient,
derived previously

Ps = vapour pressure of water at
skin temperature (mm Hg)

Pa = vapour pressure of water at
ambient temperature (mm Hg)

Present study

Condition	hc	Ps	Pa	E ($W \cdot m^{-2}$)
1	8.3	40.5	17.5	191
2	30.1	32.6	17.5	455
3	30.1	31.1	17.5	409
4	30.1	35.9	31.8	123
5	30.1	37.5	31.8	171
6	30.1	36.3	31.8	135

Radiation, R:

$$R = F_{\epsilon} F_c \sigma (T_1 - T_2) W \cdot m^{-2}$$

(Kerslake, 1972)

where F_{ϵ} = emittance factor (dimensionless)
 = 1.00 for a perfect black body
 = 0.95 for human skin
 F_c = configuration factor
 (dimensionless)
 = 0.7 for seated subject
 σ = Stefan-Boltzmann constant
 = $5.67 \cdot 10^{-8} W \cdot m^{-2} \cdot K^{-4}$
 T_1 = skin temperature ($^{\circ}K$)
 T_2 = ambient temperature ($^{\circ}K$)

Present study

Condition	$F_{\epsilon} F_c \sigma$	T_1	T_2	R ($W \cdot m^{-2}$)
1	$3.77 \cdot 10^{-8}$	307.3	293.0	58
2	$3.77 \cdot 10^{-8}$	303.4	293.0	42
3	$3.77 \cdot 10^{-8}$	302.6	293.0	38
4	$3.77 \cdot 10^{-8}$	305.1	303.0	9
5	$3.77 \cdot 10^{-8}$	305.9	303.0	12
6	$3.77 \cdot 10^{-8}$	305.3	303.0	10

Respiratory Heat Loss, Eres:

Total respiratory heat exchange = difference in enthalpy (total heat content per unit mass of dry air, J/g) between inspired and expired air

$$= (h_e - h_i)$$

$$= 98.7 - (0.658 T_a) - (14.1 P_a) \text{ J} \cdot \text{g}^{-1} \text{ dry air}$$

(Kerlake, 1972)

where T_a = ambient temperature ($^{\circ}\text{C}$)

P_a = vapour pressure of water at ambient temperature (kPa)

V_e = respiratory minute volume ($\text{l} \cdot \text{min}^{-1}$, BTPS)

$$\text{Present study, } V_e(\text{STPD}) = 60.0 \text{ l} \cdot \text{min}^{-1}$$

$$\begin{aligned} V_e(\text{BTPS}) &= V_e(\text{STPD}) \left(\frac{310}{273} \right) \left(\frac{760}{(730-47)} \right) \\ &= 1.26 V_e(\text{STPD}) = 75.6 \text{ l} \cdot \text{min}^{-1} \end{aligned}$$

Dry air is approximately 80% nitrogen, 20% oxygen.

The molecular weight of N = 14 and O = 16.

Thus, the mass of 1 mole of air is
 $(.8 \cdot 28) + (.2 \cdot 32) = 28.8 \text{ g}$.

At standard conditions, 1 mole of a gas occupies 22.4 litres.

Therefore, at these conditions, 1 litre of air weighs $28.8/22.4 = 1.29 \text{ g}$.

$$V_e(\text{STPD}) = 60.0 \text{ l} = 60 \cdot 1.29 = 77.4 \text{ g}$$

$$1 W = 1 \text{ J} \cdot \text{s}^{-1} = 60 \text{ J} \cdot \text{min}^{-1}$$

Respiratory heat loss (continued)

Present study:

Condi- tion (g·min ⁻¹)	Ta	Pa	he-hi	mass of air in- spired	he-hi ₁ (J·min ⁻¹)	he-hi (W)	(he-hi) ₂ /BSA (W·m ⁻²)
1	20	2.34	52.5	77.4	4064	68	36
2	20	2.34	52.5	77.4	4064	68	36
3	20	2.34	52.5	77.4	4064	68	36
4	30	4.24	19.2	77.4	1486	25	13
5	30	4.24	19.2	77.4	1486	25	13
6	30	4.24	19.2	77.4	1486	25	13

Respiratory heat loss (continued):

Similar estimates for the rate of respiratory heat loss may be derived from the simpler formula reported by Mitchell, J.W. (1977):

$$E_{res} = 0.023 M ((44 - P_a) + 0.61(35 - T_a)) W$$

where M = rate of metabolic heat production
previously derived (W)
P_a = vapour pressure of water at
ambient temperature (mm Hg)
T_a = ambient temperature (°C)

Present study

Condi- tion	M	P _a	T _a	(44-P _a)	(35-T _a)	E _{res} (W)	E _{res} /BSA (W·m ⁻²)
1	1072	17.5	20	26.5	15	87	46
2	1072	17.5	20	26.5	15	87	46
3	1072	17.5	20	26.5	15	87	46
4	1072	31.8	30	12.2	5	38	20
5	1072	31.8	30	12.2	5	38	20
6	1072	31.8	30	12.2	5	38	20

Solar radiation, Hsd:

Hsd = total heat gain from the sun

$$= A_d \alpha_s I_s \quad W \quad (\text{Kerslake, 1972})$$

where A_d = area of the body exposed
to solar radiation

α_s = the proportion of the
incident solar radiation

absorbed

I_s = rate of solar energy
= $678 \text{ W}\cdot\text{m}^{-2}$ for the present study
(measured from dry, wet and black
bulb temperatures, and air flow
rate)

α_s depends on the wavelength of the light source,
and the absorbance characteristics of the surface
which it strikes.

Typical values of α_s for white and black skin are
0.6 and 0.8, respectively (Kerslake, 1972).
Absorbance drops to 0.3 and 0.6, respectively for
white and black skin for light with a wavelength
of about 1 micron.

The tungsten movie lamps used as a radiant energy
energy source in the present study have a "colour
temperature" of $3,400^\circ\text{K}$.

Most of the energy emitted from such lamps is
above 4.5 microns in wavelength (Langford, 1969).
For light above 1.5 microns, absorbance is
relatively constant at 0.9. (Kerslake, 1972)

A_d varies with the orientation of the subject
with respect to the radiant energy source.

A_d has been reported to be about 20% of total
body surface area for a variety of body positions
and positions of the sun in the sky.

In the present study, A_d was assumed to be
 $0.2 \cdot 1.9 = 0.38 \text{ m}^2$.

For the four environment/clothing conditions
involving simulated solar radiation (Conditions
3 to 6):

$$Hsd = (.38) (.9) (678) = 232 \text{ W}$$

Rate of heat body heat storage, S:

The rate of heat storage in the body may be estimated from the algebraic sum of the separate factors calculated previously. The "solar" heat gain is expressed in W, and assumed to operate only over the surface of the body exposed to the movie lamps. The other factors have all been calculated in $W \cdot m^{-2}$, so must now be multiplied by BSA ($1.9 m^{-2}$) to equate all units in W.

$$S = 1.9M - 1.9W - 1.9C - 1.9E - 1.9R - (h_e - h_i)/BSA + Hsd$$

Present study:

Condi- tion	S (W)	M (W)	W (W)	C (W)	E (W)	R (W)	($h_e - h_i$)/BSA (W)	Hsd (W)
1	79	1072	268	226	321	110	68	0
2	-1425	1072	268	538	1543	80	68	0
3	-989	1072	268	496	1389	72	68	232
4	470	1072	268	108	416	17	25	232
5	251	1072	268	150	587	23	25	232
6	408	1072	268	120	464	19	25	232

Rate of increase in body temperature, dT_b/dt :

The rate of increase in mean body temperature, dT_b/dt , is related to the rate of heat storage (S) and the specific heat of body tissues (mc), usually considered to be $0.83 \text{ kcal} \cdot \text{kg}^{-1} \cdot \text{C}^{-1}$.

In the previous equations, S has been expressed in W, which is equivalent to $\text{J} \cdot \text{s}^{-1}$.

Applying the correct conversion factors, dT_b/dt for the subjects in the present study (mean body weight 71.7 kg) may be estimated as:

$$\begin{aligned} dT_b/dt \text{ (}^\circ\text{C} \cdot \text{min}^{-1}\text{)} &= \\ S(\text{J} \cdot \text{s}^{-1})(60\text{s} \cdot \text{min}^{-1})(\text{C} \cdot \text{kg}^{-1} / .83\text{kcal})(1/71.7\text{kg})(\text{kcal}/4,816\text{J}) \\ &= 2.093 \cdot 10^{-4} S \text{ (}^\circ\text{C} \cdot \text{min}^{-1}\text{)} \end{aligned}$$

For example, for subjects riding in the laboratory at 20°C wearing cotton clothing with no fans or lamps,

$$\begin{aligned} dT_b/dt &= (2.093 \cdot 10^{-4}) 79_{-1} \\ &= 1.65 \cdot 10^{-1} \text{ }^\circ\text{C} \cdot \text{min}^{-1} \end{aligned}$$

At this rate of increase, at the end of 88 minutes of exercise mean body temperature would have theoretically increased by 1.5°C .