Human temperature regulation during exercise in the heat: effects of the menstrual cycle and ambient thermal profile

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A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

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2018

ABSTRACT

Behavioural thermoregulation is the most effective means with which we regulate our body temperature at rest and during exercise. Yet, research into behavioural thermoregulation during exercise is still at an emergent stage, as it has not included females, or investigated different thermal profiles. In particular, limited studies are available to describe the behavioural and physiological differences between dry and humid heat for both sexes. Furthermore, it remains unknown whether ambient humidity or temperature alone contribute to the initiation of the behavioural responses during exercise in the heat. Therefore, the first part of this thesis investigated the effects of endogenous and exogenous female ovarian hormones on behavioural and autonomic responses, in both dry and humid heat environments matched according to the heat stress index, WBGT (**Chapter Five** and **Six**). The results from **Chapter Five** clearly show that behavioural and autonomic responses were less affected by menstrual phase, but were affected by the environmental conditions. In particular, trained women reduced their power output in order to nullify the autonomic strain from a humid heat environment. **Chapter Six** then extended this observation to (trained) women taking combined hormonal contraception, compared to eumenorrheic women in **Chapter Five**. The results from **Chapter Six** indicate that greater autonomic strain was observed in women with hormonal contraception, compared to eumenorrheic women, in both dry and humid heat, whilst the behavioural response was similar between those two groups. Furthermore, the behavioural response was different between dry and humid heat, with power output being lower in the humid heat environment compared to dry heat. The second part of this thesis investigated the effects of ambient temperature *per se* on the interaction of thermoregulatory, cardiovascular and perceptual responses to exercise (**Chapter Seven**), as well as assessing different exercise modalities (variable-intensity versus fixed-intensity exercise) and their effects on thermoregulation when the duration and average power output were matched (**Chapter Eight**). The results from **Chapter Seven** indicate that thermoregulatory and cardiovascular responses were not affected by ambient temperature but that perception was, when vapour pressure was matched between two different thermal profiles. The results from **Chapter Eight** indicate that self-pacing (behaviour) did not modulate thermoregulatory strain, when both self-paced and fixed-intensity were matched at the same exercise intensity and duration. In conclusion, this thesis extends the knowledge-base on behavioural

thermoregulation in trained women and also provides evidence that behavioural and autonomic thermoregulation is influenced more by vapour pressure than ambient temperature of the environment in men. Furthermore, the findings of this thesis confirm that behavioural thermoregulation is effective in modulating physiological strain only when there is a reduction in metabolic heat production.

ACKNOWLEDGEMENTS

“It takes a village to raise a child”. I believe this is true of a PhD student also! With that, I am deeply indebted to so many people around me. First, I am eternally grateful to all of my supervisors: Dr Toby Mündel, Professor Steve Stannard and Associate Professor James Cotter for their unconditional support throughout my PhD journey. Especially to Toby, I simply cannot thank you enough for being awesome and being supportive during the downside of my PhD and willing to give a scholarship to a student who failed half of his papers during his first year. Furthermore, I thank you for the training and the development as an independent researcher in thermoregulatory physiology. To Steve, thank you for your input and giving me the opportunity to apply my knowledge to high performance athletes. To Jim, your knowledge in thermoregulatory physiology is second to none and I sincerely enjoy your ‘kiwi as’ supervisory style, as well as showing me around the city of Dunedin. Also, I sincerely appreciate the support from Dr Zachary Schlader and Associate Professor Ahmad Munir Che Muhamed throughout my PhD journey. Equally, I sincerely appreciate the technical support provided by Dr Blake Perry, Mr John Pedley and Mr Adam Miller.

I am also eternally grateful for the support from the “4 am PhD Club” (Drs William and Emma O’Connor, Dr Matt Miller and Yanita McLeay), without such support, it would be mission impossible to complete my PhD studies. In particular, special appreciation must be given to Dr Emma O’Connor for her willingness to correct and proof read this dissertation. I will miss all of you and wish you all well in the future.

To my Massey colleagues, my master supervisor, and friends, Prof Pui Man Wai, Dr Matt Barnes, Dr Yusuke Kuroda, 榆倩學姊, Dr Darryl Cochrane, Jeremy Fraser, May, Dr Jess Dent, Ashley Petterson, Melissa Black, Rachel Gardner and Hamish Hammond thank you all for being supportive and being awesome during the hardest time of my life.

I also have to give a big shout to my study participants for their willingness to endure the discomfort in the heat. Without the help from you guys, there can be no PhD!

Lastly, to my beloved family, thank you for your support to my never ending student career.

To mom, thank you for looking after me and also encouraging me to do what I want to do in my career. To dad, you not only raised a child, but you also supported and supervised me as one of your PhD students. I am greatly appreciative of your effort and to say thank to you is not simply enough! Although I can't be your PhD student, you are still my life-time PhD supervisor and that is surely much more important than a doctoral supervisor by itself. To my lovely sister, Cecilia, thank you for your support and I wish your dream can come true. To Huixin, I wish you all the best for your PhD journey. Lastly to my lovely wife, Fei, thank you for everything, none of this would have been possible without your love and support, especially being willing to drive me to school at 3 am in the morning for my experiments without a single complaint for three consecutive years. I love you!

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LIST OF ABBREVIATIONS

A	
ANOVA	Analysis of variance
$A\text{-}VCO_2$	Arteriovenous carbon dioxide content difference
AVP	Arginine vasopressin
Ach	Acetylcholine
ATP	Adenosine triphosphate
ADP	Adenosine diphosphate
AMP	Adenosine monophosphate
au	arbitrary unit
B	
BSA	Body surface area
BMI	Body mass index
BP	Blood pressure
C	
$\dot{C}$	Convective heat lost
°C	Degree centigrade
$\dot{C}_{res}$	Respiratory conductive heat lost
CO_2	Carbon dioxide
CNS	Central nervous system
Ca^{2+}	Calcium
Cl^{-1}	Chloride
CVR	Cutaneous vascular resistance
CVC	Cutaneous vascular conductance
D	
DBP	Diastolic blood pressure
DRY	Dry heat
E	
$\dot{E}$	Evaporative heat lost
E_{max}	Maximal evaporative cooling capacity of the environment
E_{req}	Required evaporative cooling for heat balance

EF	Early follicular
eNOS	endothelial nitric oxide synthase
F	
FSH	Follicle stimulating hormone
FBF	Forearm blood flow
FVR	Forearm vascular resistance
G	
g	Gram
GnRH	Gonadotropin–releasing hormone
H	
h	Hour
h_c	Convective heat transfer
HR	Heart rate
HSI	Heat strain index
HUM	Humid heat
HSP	Heat shock protein
K	
Kg	Kilogram
K^+	Potassium
KJ	Kilojoule
Kpa	Kilopascal
L	
L	Litre
LF	Linear factor
LR	Lewis relation
LSR	Local sweat rate
M	
m	Metre
$\dot{M}$	Metabolic heat production
MAP	Mean arterial pressure
Min	Minute
ML	Mid luteal phase

mmHg	Millimeters of mercury
mmol	Millimole
N	
Na^+	Sodium
$nmoll^{-1}$	Nanomole per litre
NO	Nitric oxide
NS	Nervous system
O	
O_2	Oxygen
OCP	Oral contraception pill
OP	Oral contraception
P	
P_A	Ambient water vapour pressure
P_{Sk}	Saturated water vapour pressure at the skin
$P_{ET}CO_2$	Partial pressure of end- tidal CO_2
PL	Pleasant
PO	Power output
Q	
$\dot{Q}$	Cardiac output
*q*F	Quasi-follicular
*q*L	Quasi-luteal
R	
$\dot{R}$	Rate of heat exchange via radiation
RER	Respiratory exchange ratio
RPE	Rate of perceived exertion
rpm	Revolutions per minute
S	
S	Second
$\dot{S}$	Heat Storage
SD	Standard deviation
SBP	Systolic blood pressure
SEE	Standard error of mean
SKBF	Skin blood flow
T	

T_A	Ambient temperature
$\bar{T}_b$	Mean body temperature
TAN	Total adenine nucleotide pool
T_{core}	Core temperature
TD	Thermal discomfort
T_{rec}	Rectal temperature
TS	Thermal sensation
$\bar{T}_{sk}$	Mean skin temperature
TRP	Transient receptor potential
V	
v	Air velocity
VOP	Venous occlusion plethysmography
$\dot{V}CO_2$	Rate of carbon dioxide elimination
$\dot{V}O_2$	Rate of oxygen uptake
$\dot{V}O_2max$	Maximal oxygen uptake
W	
W	Watt
WBGT	Wet-bulb globe temperature
$\dot{W}$	Rate of heat exchange from external work
Y	
Y	Year

LIST OF PUBLICATIONS

Chapter Five

Lei TH, Stannard SR, Perry BG, Schlader ZJ, Cotter JD, Toby Mündel (2017). Influence of menstrual phase and arid *vs.* humid heat stress on autonomic and behavioural thermoregulation during exercise in trained but unacclimated women. J Physiol 595.9(2017): 2823-2837.

Chapter Five

Lei TH & Mündel T (2018). Humid heat stress affects trained female athletes more than does their menstrual phase. Temperature, DOI:10.1080/23328940.2018.1436394.

Chapter Six

Lei TH, Cotter JD, Schlader ZJ, Stannard SR, Perry BG, Barnes MJ , Mündel T (in revision). On exercise thermoregulation in females: interaction of endogenous and exogenous ovarian hormones. J Physiol.

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