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The human-clothing interface: degrading and enhancing thermal homeostasis

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THE HUMAN-CLOTHING INTERFACE: DEGRADING AND ENHANCING THERMAL HOMEOSTASIS

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Presentation overview:

• Why do workers experience exhaustion in protective clothing?
• What is homeostasis?
• Is homeostasis relevant to workers wearing protective clothing?
• Protective clothing comes with physiological costs
• Are there viable solutions to these problems?
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Aetiology of heat exhaustion

“Agents”
- Air temperature
- Air movement
- Air water vapour pressure
- Radiant heat
- Metabolic heat
- Protective clothing

“Host factors”
- Cardiovascular function
- Physical fitness
- Body mass
- Age/Gender/Race
- Form of exercise
- Acclimatisation
- Hydration state
- Electrolyte balance
- Initial core temperature

Source: Taylor (2006)
Aetiology of heat exhaustion

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Homeostasis

Claude Bernard (1876):

“It is the fixity of the *milieu intérieur* which is the condition of ... the internal environment.”

Walter Cannon (1926):

“In an open system, ... constancy is ... evidence that agencies are acting ... to maintain this constancy ... If a state remains steady it does so because any tendency towards change is automatically met by ... factors which resist the change.”
Homeostasis

Regulation of the physical and chemical status of all cells:
- these states remain within narrow ranges
- for example: blood pressure, tissue temperature, acidity

This regulation is often achieved using bodily transport systems

Supply systems that:
- supply oxygen
- supply energy and nutrients (e.g. electrolytes)
- supply water

Waste removal systems that:
- remove metabolic wastes (e.g. carbon dioxide, urea)
- remove heat
Homeostasis

Blood pressure

Blood flow

Tissue perfusion

Low flow/pressure
- Cell damage

High pressure/flow
- Membrane damage

Adequate
- Life

Absent
- Death
Homeostasis: pressure regulation

Pressure regulation

- heart rate
- stroke volume
- peripheral resistance
- endocrine renal function

mean arterial pressure

work
Homeostasis: body-fluid regulation

- Stroke volume
- Peripheral resistance
- Endocrine renal function
- Central venous pressure
- Sweating
- Work
Homeostasis: temperature regulation

Temperature regulation

- thermogenesis
- sweating
- peripheral resistance
- endocrine renal function

- mean body temperature
- work
- ambient temperature
- protective clothing
Homeostasis

Pressure regulation

Body-fluid regulation

Temperature regulation

heart rate
stroke volume
peripheral resistance
diendocrine renal function
mean arterial pressure
central venous pressure
thermogenesis
sweating
mean body temperature
ambient temperature
protective clothing

Source: Werner et al. (2008)
Presentation overview:

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Is homeostasis relevant?

Protective clothing

- Hard work
  - Oxygen delivery
    - Muscle blood flow
      - Mean arterial pressure
  - Body temperature
    - Sweating
      - Plasma volume
    - Skin blood flow
      - Vasodilatation
  - Mean arterial pressure
Is homeostasis relevant?

What happens to mean arterial pressure during rest and exercise?

Cardiac output distribution: elevated skin and muscle blood flows

Source: Taylor (2005)
Is homeostasis relevant?

How is blood pressure preserved?

Heart rate responses during seated rest (50°C, 30% relative humidity)

Source: Taylor et al. (2012)
Is homeostasis relevant?

Cardiovascular responses during exercise (40°C, 45% relative humidity)

Source: Fogarty et al. (2005)
Is homeostasis relevant?

Protective clothing

Hard work
- Oxygen delivery
- Muscle blood flow
  - Mean arterial pressure

Hot environment
- Body temperature
  - Sweating
    - Plasma volume
  - Skin blood flow
    - Vasodilatation
    - Central venous pressure
    - Mean arterial pressure
Is homeostasis relevant?

How do we dissipate heat in hot environments?

Sweat production and evaporative cooling

Source: Taylor (2005)
Is homeostasis relevant?

What happens with prolonged sweating?

Changes in serum osmolality during progressive dehydration

*Source:* Taylor *et al.* (2009)
Is homeostasis relevant?

What happens to core temperature during dehydration?

Core temperature elevation with gradual dehydration during steady-state work

Source: Sawka and Coyle (1999)
Is homeostasis relevant?

Protective clothing

Hard work

Hot environment

Body temperature

Sweating

Skin blood flow

Muscle blood flow

Plasma volume

Vasodilatation

Oxygen delivery

Mean arterial pressure

Central venous pressure

Mean arterial pressure
Is homeostasis relevant?

What happens during hard physical work?

Muscle blood flow and heat production both increase

Source: Taylor (2005)
Is homeostasis relevant?

Protective clothing

Hard work

Oxygen delivery

Muscle blood flow

Mean arterial pressure

Body temperature

Hot environment

Sweating

Plasma volume

Central venous pressure

Mean arterial pressure

Skin blood flow

Vasodilatation
Is homeostasis relevant?

At least three homeostatic process are adversely affected:

- mean arterial pressure regulation
- central venous pressure regulation
- mean body temperature regulation

Two of these involve the cardiovascular system

The primary cause of exercise-associated heat exhaustion, when wearing protective clothing, is cardiovascular insufficiency
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The physiological costs of protective clothing

Ideal for heat dissipation  Impaired heat dissipation  Impossible heat dissipation

Source: Taylor (2005)
The physiological costs of protective clothing

What happens to skin temperatures during fire exposure?
The physiological costs of protective clothing

<table>
<thead>
<tr>
<th>Site</th>
<th>Ensemble</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td>$T_{air}$</td>
<td>145.05</td>
</tr>
<tr>
<td>$T_{chest}$</td>
<td>41.05</td>
</tr>
<tr>
<td>$T_{i-shirt}$</td>
<td>53.50</td>
</tr>
<tr>
<td>$T_{o-shirt}$</td>
<td>59.40</td>
</tr>
<tr>
<td>$T_{tunic}$</td>
<td>81.70</td>
</tr>
<tr>
<td>$T_{leg}$</td>
<td>46.65</td>
</tr>
<tr>
<td>$T_{i-trouser}$</td>
<td>58.90</td>
</tr>
<tr>
<td>$T_{pant}$</td>
<td>83.35</td>
</tr>
</tbody>
</table>

Skin temperature changes: flashover exposure

*Source: Fogarty et al. (2005)*
The physiological costs of protective clothing

How are physiological responses affected by protective clothing?
The physiological costs of protective clothing

Skin temperature changes: working in the heat

Control
Clothed

Source: Fogarty et al. (2004)
The physiological costs of protective clothing

Comparing six thermal protective ensembles

Source: Kerry et al. (2009)
The physiological costs of protective clothing

Core temperature changes: working in the heat

Source: Kerry et al. (2009)
The physiological costs of protective clothing

What is the metabolic cost of protective clothing?

Source: Taylor et al. (2012)
The physiological costs of protective clothing

Metabolic cost of wearing personal protective clothing and equipment

Source: Taylor et al. (2012)
The physiological costs of protective clothing

Comparing three chemical and biological protective ensembles

Severely impaired heat dissipation  Now with added heat production

*Source: van den Heuvel et al. (2007)*
The physiological costs of protective clothing

Core temperature and heart rate responses

Source: van den Heuvel et al. (2007)
The physiological costs of protective clothing

Consequence

Reduced work tolerance times

Source: van den Heuvel et al. (2007)
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  • under-armour fabrics and garments
  • vapour-permeable layer (moisture barrier)
  • auxiliary cooling
Evaporation is impaired in the presence of clothing

Source: Taylor (2005)
Under-armour fabrics and garments

Comparing five undergarment (t-shirt) ensembles

- Ensemble A: no t-shirt
- Ensemble B: 100% cotton t-shirt (Walkabout®)
- Ensemble C: 100% merino woollen t-shirt (Driza-Bone®)
- Ensemble D: 100% polyester t-shirt (Under Armour®)
- Ensemble E: hybrid torso shirt (100% merino wool; Rammite.com®) with shirt collar and long sleeves (75% cotton, 25% polyester)

Source: van den Heuvel et al. (2010)
Under-armour fabrics and garments

Subjects:
- Eight males: 24.6 y (±5.95), 76.93 kg (±8.35), 1.79 m (±0.06)

Exercise protocol:
- Phase I (120 min): walking on treadmill at 4 km.h⁻¹ (0% grade)
- Phase II (20 min): alternate running-walking protocol:
  - 2 min walking at 4 km.h⁻¹ (0% grade)
  - 2 min running at 10 km.h⁻¹ (0% grade)

Environmental conditions:
- Hot-dry conditions: 41.2°C (±0.2), 29.8% (±4.1) relative humidity
- Constant wind velocity: 4 km.h⁻¹

Clothing ensembles:
- Camouflage combat uniform (75% cotton; 25% polyester) with combat body armour and helmet (total mass: 7.2 kg)
Under-armour fabrics and garments

Heart rate responses

Entire trial

Phase II: alternate walk and run

Source: van den Heuvel et al. (2010)
Under-armour fabrics and garments

Thermal responses

Source: van den Heuvel et al. (2010)
### Under-armour fabrics and garments

#### Water vapour pressure gradients (kPa) within ensembles

<table>
<thead>
<tr>
<th>Sites</th>
<th>Ensemble A</th>
<th>Ensemble B</th>
<th>Ensemble C</th>
<th>Ensemble D</th>
<th>Ensemble E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chest: layer 1</td>
<td>1.25</td>
<td>1.61</td>
<td>1.19</td>
<td>1.06</td>
<td>1.36</td>
</tr>
<tr>
<td>Chest: layer 2</td>
<td>-</td>
<td>-0.38</td>
<td>0.06</td>
<td>0.15</td>
<td>-</td>
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<tr>
<td>Back: layer 1</td>
<td>1.85</td>
<td>2.22</td>
<td>2.30</td>
<td>1.74</td>
<td>1.88</td>
</tr>
<tr>
<td>Back: layer 2</td>
<td>-</td>
<td>-0.50</td>
<td>-1.64</td>
<td>-1.15</td>
<td>-</td>
</tr>
</tbody>
</table>

*Source: van den Heuvel et al. (2010)*
Under-armour fabrics and garments

Predictions prior to performing these experiments:
- fewer clothing layers should be more beneficial:
  Ensembles A and E would be superior
- good wicking fabrics should facilitate cooling and comfort:
  Ensembles B and C would be superior

None of the strain indices supported these predictions

Why?
- Strain was more powerfully dictated by other stresses:
  - dry heat - metabolic heat production - clothing - body armour

Regardless of the fabric, or even presence of an undergarment, dry and evaporative heat transfers remained equivalent: no benefit
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  - vapour-permeable layer (moisture barrier)
  - auxiliary cooling
Vapour-permeable layer (moisture barrier)

Impermeable layers prevent evaporative cooling

Source: Taylor (2005)
Vapour-permeable layers are ineffective when working in the heat

Source: Taylor (2005)
Vapour-permeable layer (moisture barrier)

Comparing thermal protective clothing with and without moisture barriers

Source: Kerry et al. (2009)
Vapour-permeable layer (moisture barrier)

Thermal responses

Source: Kerry et al. (2009)
Vapour-permeable layer (moisture barrier)

Vapour-pressure responses

Source: Kerry et al. (2009)
Vapour-permeable layer (moisture barrier)

Outcomes:

- microclimate next to the skin was hotter
- microclimate next to the skin has greater water-vapour pressure

These states impair both dry and evaporative heat losses

Do these layers prevent scald burns?

- this propositions is debatable
- many believe these burns are caused super-heating sweat

The utility of these layers in protective clothing is questionable
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Auxiliary cooling

Counteracting thermal strain with auxiliary liquid cooling

Source: Caldwell et al. (2012)
Auxiliary cooling

Cooling to match skin temperatures

*Source: Caldwell et al. (2012)*
Auxiliary cooling

Thermal and heart rate responses

Source: Caldwell et al. (2012)
Auxiliary cooling

Counteracting thermal strain with auxiliary air cooling

Source: van den Heuvel et al. (2007)
Auxiliary cooling

Thermal and heart rate responses

Source: van den Heuvel et al. (2007)
Auxiliary cooling

Outcomes:

• some auxiliary cooling systems absolutely work:
  • water-based systems
  • but they are cumbersome and require a power supply

• some cooling systems are much less effective:
  • air-based systems
  • unless the air flow is very high
  • also require power supply

• some cooling systems have very limited utility:
  • phase-change systems: materials and fabrics
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