HEAT LOAD LIMITATIONS UNDER NORMAL AND STRESS CONDITIONS

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HEALTH EFFECTS OF HEAT STRESS

- Functional exhaustion of thermoregulatory mechanisms is typically manifested via two pathological conditions:
  - thermal exhaustion
  - heat stroke
    - work/exercise induced
      - Tc: >40°C
      - neurological dysfunction

Gabrielle Andersen, Los Angeles, 1984
EFFECTS OF MICROWAVE EXPOSURE

- Squirrel monkeys exposed to 2450-MHz continuous-wave microwaves for 40 h/week for 15 weeks
  - **No effect** of microwave exposure:
    - metabolic rate, core temperature, sweating
  - **Significant effect** of microwave exposure:
    - skin temperature

Adair et al., Bioelectromagnetics, 1985
EFFECTS OF RADIOFREQUENCY EXPOSURE

- 45-min dorsal exposure to 450 and 2450 MHz continuous-wave radio-frequency energy
  - 7 adults
  - 24°C, 28°C, and 31°C
  - 2 peak power densities (equivalent to normalized peak surface SARs of 6.0 and 7.7 W/kg)

Adair et al., Bioelectromagnetics, 1998-99
EFFECTS OF RADIOFREQUENCY EXPOSURE

- **No effect** of radiofrequency:
  - metabolic heat production
  - esophageal temperature

- **Significant effect** of radiofrequency:
  - skin temperature

Adair et al., Bioelectromagnetics, 1998-99
EFFECTS OF RADIOFREQUENCY EXPOSURE

- 45-min dorsal exposure to 2450 MHz CW radio-frequency energy
  - 7 adults
  - 24°C, 28°C, and 31°C
  - 2 peak power densities (equivalent to normalized peak surface SARs of 11 and 15.4 W/kg)

Adair et al., Bioelectromagnetics, 2001
EFFECTS OF MAGNETIC FIELD EXPOSURE

- 7 healthy young males
- Strong extremely low frequency magnetic field (16.7 Hz, 0.2 mT) continuously applied between 6 pm and 2 am
- **No effect** on core temperature

Griefahn et al., Bioelectromagnetics, 2001
MICROWAVE EXPOSURE & BRAIN METABOLISM

- Exposure to 591 MHz radiation at 13.8 mW/cm² for 0.5, 1.0, 3.0, and 5.0 min

- **No effect** on brain temperature

- **Significant effects** on CP and ATP

Sanders et al., Bioelectromagnetics, 1984
THERMAL EFFECTS OF EMF EXPOSURE

- Human model subjected to an 80-MHz EMF at a power density of 32.5 mW/cm²

Spiegel et al., Bioelectromagnetics, 1980
EXISTING PRACTICE

- The American Conference of Governmental Industrial Hygienists proposed the **Threshold Limit Values** to manage the level of thermal strain experienced by workers
  - work-rest allocations that consider environmental conditions (WBGT) adjusted for activity level and clothing insulation
  - primary goal: preventing **core temperature** from exceeding predefined thresholds which are adjusted to account for the acclimation status of the worker
    - upper limit Tc allowed in non-acclimated workers: **38.0°C**
    - upper limit Tc allowed in acclimated workers: **38.5°C**
ACGIH TLV’s for hot environments for physically fit and acclimatized individuals wearing light summer clothing

<table>
<thead>
<tr>
<th>Work-Rest Regimen</th>
<th>Light</th>
<th>Moderate</th>
<th>Heavy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous Work</td>
<td>30 °C</td>
<td>26.67 °C</td>
<td>25 °C</td>
</tr>
<tr>
<td>75% Work 25% Rest, each hour</td>
<td>30.56 °C</td>
<td>27.78 °C</td>
<td>25.56 °C</td>
</tr>
<tr>
<td>50% Work 50% Rest, each hour</td>
<td>31.67 °C</td>
<td>29.44 °C</td>
<td>27.78 °C</td>
</tr>
<tr>
<td>25% Work 75% Rest, each hour</td>
<td>32.2 °C</td>
<td>31.11 °C</td>
<td>30 °C</td>
</tr>
</tbody>
</table>
CORE TEMPERATURE

- Core temperature is the temperature of deep structures of the body such as the liver
  - measurement in the rectum is the traditional gold standard measurement, however it responds with a significant time delay
  - esophageal temperature is preferable due to its fast response time, however it is relatively invasive
  - visceral temperature is used infrequently and responds with a time delay
  - brain, jugular, and bladder temperatures are rarely used due to their invasiveness
VARIATION IN CORE TEMPERATURE

Rumana et al., Crit Care Med, 1998

Verlooy et al., Acta Neurochir, 1995
CHANGES IN CORE TEMPERATURE

Flouris & Cheung, JAP, 2009
CHANGES IN CORE TEMPERATURE

Flouris & Cheung, JAP, 2009
CLOTHING

- 4x15 min work bouts at 400 W

35 °C
15% RH

Poirier et al., JOEH, In Press
CLOTHING

- 4x15 min work bouts at 400 W

35 °C 15% RH
Do we really understand the risk using core temperature? Raising a red flag!
Do we really understand the risk using core temperature? Raising a red flag!

![Graph showing change in mean body temperature for different conditions.](image)

- CE1_{STD}
- CE4_{AFR}
- CE9_{AFR}

Actual - 2 hours
Estimated - 2 hours
Estimated - 8 hours

38.5°C
HEAD THERMOREGULATION
RADIOFREQUENCY & BRAIN METABOLISM

Volkow et al., JAMA, 2011
**RADIOFREQUENCY & HEAD THERMOREGULATION**

- Highest temperature after 30 min radiation exposure:
  - adult brain: 37.112°C
  - child brain: 37.118°C

Wessapan et al., JHT, 2012
HEAD THERMOREGULATION AT REST

- Average brain temperature at rest: \( \sim 37^\circ C \)
  - heat is heterogeneously distributed in the brain
    - local temperature depends on the proportion between the regional **metabolic rate** and **cerebral blood flow**

Mariak et al., 1999, JAP

~1.5 mmol O\(_2\)·g\(^{-1}\)·min\(^{-1}\)

Madsen et al., 1993, JAP

~0.6 j·g\(^{-1}\)·min\(^{-1}\)

Yablonskiy et al., 2000, PNAS

Nybo et al., 2002, J Physiol

~0.5 ml·g\(^{-1}\)·min\(^{-1}\)

~0.6 j·g\(^{-1}\)·min\(^{-1}\)

~0.3 °C

arterio-venous temp. difference

heat balance

cerebral heat production
## CONSIDERATIONS

### Head dimensions

<table>
<thead>
<tr>
<th></th>
<th>Adult (cm)</th>
<th>7 years old child (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head length</td>
<td>18.8</td>
<td>17.3</td>
</tr>
<tr>
<td>Head breadth</td>
<td>16</td>
<td>14.9</td>
</tr>
<tr>
<td>Head height</td>
<td>23.7</td>
<td>20.8</td>
</tr>
</tbody>
</table>

### Dielectric properties of tissues at 900 MHz

<table>
<thead>
<tr>
<th>Type of tissue</th>
<th>$\varepsilon_r$</th>
<th>$\sigma$ (S/m)</th>
<th>$\varepsilon_r$</th>
<th>$\sigma$ (S/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skin</td>
<td>41.41</td>
<td>0.87</td>
<td>42.47</td>
<td>0.89</td>
</tr>
<tr>
<td>Fat</td>
<td>11.33</td>
<td>0.11</td>
<td>12.29</td>
<td>0.12</td>
</tr>
<tr>
<td>Bone</td>
<td>20.79</td>
<td>0.34</td>
<td>21.97</td>
<td>0.36</td>
</tr>
<tr>
<td>Brain</td>
<td>45.805</td>
<td>0.765</td>
<td>46.75</td>
<td>0.78</td>
</tr>
</tbody>
</table>

### Thermal properties of tissues

<table>
<thead>
<tr>
<th>Tissue</th>
<th>$\rho$ (kg/m$^3$)</th>
<th>$k$ (W/m·°C)</th>
<th>$C$ (J/kg·°C)</th>
<th>$Q_{\text{met}}$ (W/m$^3$)</th>
<th>$\omega_B$ (1/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skin</td>
<td>1125</td>
<td>0.42</td>
<td>3600</td>
<td>1620</td>
<td>0.02</td>
</tr>
<tr>
<td>Fat</td>
<td>916</td>
<td>0.25</td>
<td>3000</td>
<td>300</td>
<td>$4.58 \times 10^{-4}$</td>
</tr>
<tr>
<td>Bone</td>
<td>1990</td>
<td>0.37</td>
<td>3100</td>
<td>610</td>
<td>$4.36 \times 10^{-4}$</td>
</tr>
<tr>
<td>Brain</td>
<td>1038</td>
<td>0.535</td>
<td>3650</td>
<td>7100</td>
<td>$8.83 \times 10^{-3}$</td>
</tr>
</tbody>
</table>
EFFECTS OF SEX, AGE, FITNESS AND DISEASE THERMOREGULATION
Sex differences in thermoeffectort responses during exercise at fixed requirements for heat loss

Daniel Gagnon and Glen P. Kenny

Age-Related Decrements in Heat Dissipation during Physical Activity Occur as Early as the Age of 40

Joanie Larose¹, Pierre Boulay², Ronald J. Sigal³, Heather E. Wright¹, Glen P. Kenny¹*

PLoS ONE 8(12): e83148. doi:10.1371/journal.pone.0083148
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![Graph showing rate of required evaporative heat loss (W) over time (min).]
AGE & DIABETES

- 26 young (23±3 years)
- 25 older (63±5 years)
- 11 T2D (59±9 years)

3 hours

43 °C
30% RH

Kenny et al., Under Preparation
AGE & DIABETES

Kenny et al., Under Preparation
AGE & DIABETES
THRESHOLDS FOR WORK IN THE HEAT

- 87 men
- 24 women
- 4x15 min work bouts at 400 W

Flouris et al., Under Preparation
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