Chapter 15

Factors Affecting Physiologic Function: The Environment and Special Aids to Performance

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Objectives

1. Explain the statement: The hypothalamus plays the most important role in regulating thermal balance.

2. Name four physical factors that contribute to heat exchange during rest and exercise.

3. Describe how the circulatory system serves as a “workhorse” for thermoregulation.

4. List desirable clothing characteristics for use during exercise in cold and warm weather.

5. Describe how cardiac output, heart rate, and stroke volume respond during submaximal and maximal exercise with environmental heat stress.

6. Describe circulatory adjustments that maintain blood pressure during hot-weather exercise.

7. Quantify fluid loss during hot-weather exercise.
8. Identify the physiologic consequences of dehydration

9. Explain how acclimatization, training, age, gender, and body fat modify heat tolerance during exercise

10. Identify factors that comprise the Heat Stress Index

11. Explain the purpose of the Wind Chill Index

12. Describe the physiologic adjustments to cold stress.

13. Outline the effects of increasingly higher altitudes on (1) partial pressure of oxygen in ambient air, (2) saturation of hemoglobin with oxygen in the pulmonary capillaries, and (3) VO$_{2\text{max}}$.

14. Describe immediate and long-term physiologic adjustments to altitude exposure.

15. Identify at least three of the most common types of ergogenic aids.
Thermoregulation

- Normal body temperature fluctuates several degrees during the day in response to physical activity, emotions, and ambient temperature variations.
- Body temperature exhibits diurnal fluctuations:
  - Lowest temperatures occur during sleep
  - Slightly higher temperatures persist when awake
# Thermoregulation

## Table 15.1: Mechanisms for Temperature Regulation

<table>
<thead>
<tr>
<th>Stimulated by Cold</th>
<th>Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decreases heat loss</td>
<td>Vasoconstriction of skin vessels; postural reduction of surface area (curling up)</td>
</tr>
<tr>
<td>Increases heat production</td>
<td>Shivering and increased voluntary activity; increased thyroxine and epinephrine secretion</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>Stimulated by Heat</th>
<th>Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increases heat loss</td>
<td>Vasodilation of subcutaneous skin vessels; sweating</td>
</tr>
<tr>
<td>Decreases heat production</td>
<td>Decreased muscle tone and voluntary activity; decreased thyroxine and epinephrine secretion</td>
</tr>
</tbody>
</table>
Thermal Balance

- Thermal balance functions
  - Alter heat transfer to the periphery
  - Regulate evaporative cooling
  - Vary the rate of heat production
Thermal Balance

- Radiation
- Conduction
- Convection
- Evaporation

Body heat content

Heat loss

37°C

Daily variation

BMR
Muscular activity
Hormones
Thermic effect of food
Postural changes
Environment

Heat gain
Heat Loss From the Body

- Body temperature maintained by balance of heat production and loss
- Shivering rapidly consumes calories.
- Heat loss occurs primarily through skin.
Four mechanisms of heat loss:

1. Radiation
   - Heat given off to cooler air
   - Primary method of heat loss
2. Conduction
   - Direct contact with colder object
3. Convection
   - Loss of heat by air blowing over skin
4. Evaporation
   - Conversion of liquid on skin to vapor
Hypothalamic Regulation of Body Temperature

- The hypothalamus contains the central coordinating center for temperature regulation.
  - Regulates temperature within a range of 37°C ± 1°C

- The hypothalamic regulatory center plays the most important role in maintaining thermal balance.

- Temperature-regulating mechanisms are activated by:
  - Thermal receptors in the skin provide peripheral input to the hypothalamic central control center.
  - Temperature changes in blood
Cold Stress

- Three integrated factors regulate body temperature during cold exposure:
  - Vascular adjustments
  - Muscular activity (shivering)
  - Hormonal output

Heat Stress

- Thermoregulatory mechanisms primarily protect against overheating
- Four potential avenues for heat exchange when exercising:
  - Radiation
  - Conduction
  - Convection
  - Evaporation: Provides the major physiologic defense against overheating
Heat Stress

- Solar radiation
- Air temperature and humidity
- Evaporation (respiratory)
- Convection
- Radiation
- Sky: thermal radiation
- Evaporation (sweat)
- Skin/blood convection
- Metabolic storage
- Muscle blood flow convection
- Contracting muscle
- Mechanical work
- Conduction

Reflected solar radiation
Ground: thermal radiation
Ground: conduction
Heat Loss in High Humidity

- Sweat evaporation from the skin depends on three factors:
  - Surface exposed to the environment
  - Temperature and relative humidity of ambient air
    - Relative humidity exerts the greatest impact on the effectiveness of evaporative heat loss (90-90 rule)
  - Convective air currents around the body

- Sweat does not cool the skin; rather, skin cooling occurs when sweat evaporates.
Effects of Humidity

- Sweat can cool the body only if it evaporates.
- No sweat evaporates in high humidity.
- The higher the humidity, the lower the temperature at which heat risk begins.
Integration of Heat-Dissipating Mechanisms

- **Heat dissipation** involves the integration of three physiologic mechanisms: circulation, evaporation, and hormonal adjustments.
  - **Circulation**: The circulatory system serves as “workhorse” for thermal balance.
  - **Evaporation**: Sweating begins several seconds after initiation of vigorous exercise.
  - **Hormonal adjustments**: Heat stress initiates hormonal adjustments to conserve electrolytes and fluid lost in sweat.
Effects of Clothing on Thermoregulation

- **Cold-Weather Clothing**
  - The ideal winter garment in cold, dry weather blocks air movement but also allows water vapor from sweating to escape through clothing for subsequent evaporation.
  - Gortex® is a great material to purchase.

- **Warm-Weather Clothing**
  - Dry clothing, no matter how lightweight, retards heat exchange more than the same clothing soaking wet.
  - Of all athletic uniforms and equipment, football gear presents the greatest barrier to heat dissipation.
Exercise in Heat

- **Circulatory adjustments**
  - Two competitive cardiovascular demands exist when exercising in hot weather:
    - Oxygen delivery to active muscles increases
    - Peripheral blood flow to the skin increases

- Cardiac output remains similar during submaximal exercise, but the heart’s stroke volume becomes smaller.

- Maximal cardiac output and aerobic capacity decrease during exercise in the heat because the compensatory increase in heart rate does not offset the decrease in stroke volume.
Exercise in Heat (Cont.)

- **Vascular constriction and dilation**
  - Adequate skin and muscle blood flow during heat stress occurs at the expense of other tissues that temporarily compromise their blood supply.

- **Maintaining blood pressure**
  - Arterial blood pressure remains stable during exercise in heat because visceral vasoconstriction increases total vascular resistance.
  - Circulatory regulation and maintenance of muscle blood flow take precedence over temperature regulation.
Water Loss in the Heat

Water Loss Per Hour

Moderate Activity
- 0.4 qt.
- 0.1 gal.
- 0.378 L

0.75 qt.
0.186 gal.
0.71 L

1.0 qt.
0.25 gal.
0.946 L

1.5 qt.
0.375 gal.
1.42 L

Light Activity
- 0.25 qt.
- 0.063 gal.
- 0.237 L

0.4 qt.
0.1 gal.
0.378 L

0.75 qt.
0.186 gal.
0.71 L

1.0 qt.
0.25 gal.
0.946 L

Rest
- 0.05 qt.
- 0.0125 gal.
- 0.047 L

0.1 qt.
0.025 gal.
0.095 L

0.25 qt.
0.063 gal.
0.237 L

0.6 qt.
0.15 gal.
0.567 L

Air Temperature
- 80°F
- 26.7°C
- 90°F
- 32.2°C
- 100°F
- 37.8°C
- 110°F
- 43.3°C
Consequences of Dehydration

- Any degree of dehydration impairs physiologic function and thermoregulation.

- When plasma volume decreases as dehydration progresses, peripheral blood flow and sweating rate decrease to make thermoregulation more difficult.

- Premature fatigue occurs from reduced plasma volume that increases heart rate, perception of effort, and core temperature.

- Loss of plasma volume does the following:
  - Initiates increases in systemic vascular resistance
  - Reduces skin blood flow
Consequences of Dehydration

Seven factors affect sweat-loss dehydration:

1. Exercise intensity
2. Exercise duration
3. Environmental temperature
4. Solar load
5. Wind speed
6. Relative humidity
7. Clothing
Water Replacement and Rehydration

- Adequate fluid replacement sustains evaporative cooling of acclimatized humans.
- Properly scheduling fluid replacement maintains plasma volume so that circulation and sweating progress optimally.
- A well-hydrated athlete always functions at a higher physiologic and performance level than a dehydrated one.
Two Factors Affecting Heat Tolerance

- **Acclimatization**
  - Repeated exposure to hot environments, when combined with exercise, improves capacity for exercise with less discomfort during heat stress
  - Optimal acclimatization necessitates adequate hydration

- **Exercise training**
  - Exercise training alone increases sweating response sensitivity and capacity so sweating begins at a lower core temperature
# Factors Affecting Heat Tolerance

## Table 15.4

<table>
<thead>
<tr>
<th>ACCLIMATIZATION RESPONSE</th>
<th>EFFECT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improved cutaneous blood flow</td>
<td>Transports metabolic heat from deep tissues to the body’s shell</td>
</tr>
<tr>
<td>Effective distribution of cardiac output</td>
<td>Appropriate circulation to skin and muscles to meet demands of metabolism and thermoregulation; greater stability in blood pressure during exercise</td>
</tr>
<tr>
<td>Lowered threshold for start of sweating</td>
<td>Evaporative cooling begins early in exercise</td>
</tr>
<tr>
<td>More effective distribution of sweat over skin surface</td>
<td>Optimum use of effective surface for evaporative cooling</td>
</tr>
<tr>
<td>Increased sweat output</td>
<td>Maximizes evaporative cooling</td>
</tr>
<tr>
<td>Lowered sweat’s salt concentration</td>
<td>Dilute sweat preserves electrolytes in extracellular fluid</td>
</tr>
</tbody>
</table>
Factors Affecting Heat Tolerance

- **Age**
  - Little age-related effects exist for thermoregulatory capacity or acclimatization to heat stress.
  - Older adults do not recover from dehydration as readily from reduced thirst drive.
  - Prepubescent children show a lower sweating rate and higher core temperature during heat stress.
  - Children take longer to acclimate to heat.
  - Children exposed to environmental heat stress should exercise at a reduced intensity and receive additional time to acclimate.
Factors Affecting Heat Tolerance

- Gender
  - Women and men equally tolerate physiologic and thermal stress of exercise when matched for fitness and acclimatization levels
  - Gender differences occur for the following four thermoregulatory mechanisms:
    1. Sweating
    2. Evaporative versus circulatory cooling
    3. Body surface area-to-mass ratio
    4. Menstruation
Excess body fat

- Excess body fat negatively impacts exercise performance in hot environments.
- Fat’s specific heat exceeds that of muscle tissue and subsequently insulates the body’s shell to retard heat conduction to the periphery.
- Large, over-fat persons possess a smaller body surface area-to-mass ratio for sweat evaporation compared with leaner, smaller persons.
- Excess body fat directly adds to energy expended in weight-bearing activities.
Exercise in the Cold

- Human exposure to extreme cold produces considerable physiologic and psychological challenges.
- The body loses heat about two to four times faster in cool water compared with air at the same temperature.
- Metabolic heat generated by muscular activity contributes to thermoregulation during cold stress.
- Individual differences in body fat content exert a considerable effect on physiologic function in a cold environment during rest and exercise.
Acclimatization to Cold

- Humans adapt more successfully to chronic heat exposure than regular cold exposure.
- Increased heat production does not accompany body heat loss, and individuals regulate at a lower core temperature in the cold.
- Repeated cold exposure of the hands or feet brings about blood flow increases through these areas during cold stress.
Exercise at Altitude

- The density of air decreases progressively with ascents above sea level.
- The $\text{PO}_2$ decreases proportionately to the decrease in barometric pressure upon ascending to higher elevations.
- Reduced $\text{PO}_2$ and accompanying arterial hypoxia precipitates the immediate physiologic adjustments to altitude and longer-term process of acclimatization.
# Exercise at Altitude

## Table 15.6  Immediate and Longer Term Adjustments to Altitude Hypoxia

<table>
<thead>
<tr>
<th>SYSTEM</th>
<th>IMMEDIATE</th>
<th>LONGER-TERM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulmonary Acid–Base</td>
<td>Hyperventilation</td>
<td>Hyperventilation</td>
</tr>
<tr>
<td></td>
<td>Body fluids become more alkaline due to reduced CO₂ (H₂CO₃) with hyperventilation</td>
<td>Excretion of base (HCO₃⁻) via the kidneys with reduced alkaline reserve</td>
</tr>
<tr>
<td>Cardiovascular</td>
<td>Increased submaximal heart rate</td>
<td>Submaximal heart rate remains elevated</td>
</tr>
<tr>
<td></td>
<td>Increased submaximal cardiac output</td>
<td>Submaximal cardiac output falls to or below sea-level values</td>
</tr>
<tr>
<td></td>
<td>Stroke volume remains the same or lowers slightly</td>
<td>Stroke volume lowers</td>
</tr>
<tr>
<td></td>
<td>Maximum cardiac output remains the same or lowers slightly</td>
<td>Maximum cardiac output lowers</td>
</tr>
<tr>
<td>Hematologic</td>
<td></td>
<td>Decreased plasma volume</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Increased hematocrit</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Increased hemoglobin concentration</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Increased total number of red blood cells</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Possible increased capillarization of skeletal muscle</td>
</tr>
<tr>
<td>Local</td>
<td></td>
<td>Increased red-blood-cell 2,3-DPG</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Increased mitochondria</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Increased aerobic enzymes</td>
</tr>
</tbody>
</table>

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Oxygen Loading at Altitude

- The inherent nature of the oxyhemoglobin dissociation curve dictates only a small change in hemoglobin’s percentage saturation with decreasing \( \text{PO}_2 \) until about 3048 m (10,000 ft).
- In the transition from moderate to higher elevations, values for alveolar oxygen partial pressure exist on the steep part of the oxyhemoglobin dissociation curve, reducing hemoglobin oxygenation dramatically and negatively impacts even moderate aerobic activities.
Altitude Acclimatization

- The adaptive responses in physiology and metabolism that improve tolerance to altitude hypoxia.

- Acclimatization adjustments occur progressively to each higher elevation, and full acclimatization requires time.

- Immediate adjustments:
  - Hyperventilation triggered by increased respiratory drive
  - Increased blood flow (cardiac output) during rest and submaximal exercise
Fluid Loss at Altitude

- A depressed thirst sensation at altitude negatively affects body fluid balance.
- The cool, dry air in mountainous regions causes considerable body water to evaporate as air warms and moistens the respiratory passages.
- Respiratory fluid loss often leads to moderate dehydration and accompanying symptoms of dryness of the lips, mouth, and throat.
Altitude-Related Medical Problems

- **Acute mountain sickness (AMS):** Relative benign condition that becomes exacerbated by exercise in the first few hours of exposure; treatment usually involves rest and gradual acclimatization.

- **High-altitude pulmonary edema (HAPE):** Involves fluid accumulation in the brain and lungs; requires immediate descent to lower altitude on a stretcher or flown to safety.
Altitude-Related Medical Problems

- **High-altitude cerebral edema (HACE):** Possible fatal neurological syndrome that develops within hours or days in people with AMS; requires immediate decent to lower altitude and supplemental oxygen administration.

- **High Altitude Retinal Hemorrhage (HARH):** Hemorrhage in the macula of the eye produces irreversible visual defects; immediate decent to a lower elevation is mandatory treatment with supplemental oxygen or use of a hyperbaric chamber.
Exercise Capacity at Altitude

- **Aerobic capacity**
  - Small declines in VO$_{2\text{max}}$ become noticeable at an altitude of 589 m and thereafter, arterial desaturation decreases VO$_{2\text{max}}$ by 7-9% per 1000-m altitude increase to 6300 m, where aerobic capacity declines at a more rapid, nonlinear rate.

- **Circulatory factors**
  - Reduced circulatory efficiency in moderate and strenuous exercise offsets benefits of acclimatization.
  - Reduced maximum exercise blood flow results from the combined effect of decreased maximum heart rate and maximum stroke volume.
**Exercise Capacity at Altitude**

- **Exercise performance**
  - Altitude has no adverse effect on events <2 minutes
  - The threshold for decrements in events lasting 2-5 minutes is 1600 m, while 600-700-m altitude induces poorer performance in events longer than 20 minutes
  - The small improvements in endurance at altitude during acclimatization probably relate to:
    - Increases in minute pulmonary ventilation
    - Increases in arterial oxygen saturation
    - A blunted lactate response in exercise
Altitude Training and Sea-Level Performance

- Sea-level aerobic capacity generally does not improve after living at altitude.
- Some physiologic changes produced during prolonged altitude exposure actually negate adaptations that could improve exercise performance upon return to sea level.
- Exposure to 2300 m and higher makes it nearly impossible for athletes to train at the same intensity as sea level.
- “Live high, train low”
Physiologic Agents to Enhance Exercise Performance

- **RBC reinfusion** (also called induced erythrocythemia, blood boosting, or blood doping)

  - Requires withdrawal of between 1-4 units of a person’s blood; plasma is removed and immediately reinfused and the packed RBCs are frozen for storage; reinfusion occurs 7 days before endurance competition.

  - Increases hematocrit and hemoglobin levels by 8-20% and increases hemoglobin concentration for men from 15 g per dL of blood to 19 g per dL.

  - Research generally confirms physiologic and performance improvements with RBC reinfusion.
Physiologic Agents to Enhance Exercise Performance (Cont.)

- **Hormonal blood boosting**
  - Erythropoietin, a hormone produced by the kidneys, stimulates bone marrow to increase RBC production.

- **Warm-up**
  - Enables the performer to prepare either physiologically or psychologically for an event and reduces likelihood of joint and muscle injury.
  - Two categories:
    - General warm-up
    - Specific warm-up
Physiologic Agents to Enhance Exercise Performance

- **Breathing hyperoxic gas**
  
  - Oxygen-enriched gas mixtures used to enhance the blood’s oxygen-carrying capacity, thus facilitating recovery from prior exercise.
  
  - Breathing hyperoxic gas during submaximal and maximal aerobic exercise enhances endurance performance.
Physiologic Agents to Enhance Exercise Performance

(A) Pedal revolutions vs. time
- Green diamond: 100% oxygen
- Red circle: Room air

(B) VO_2 vs. time
- Green diamond: 100% oxygen
- Red circle: Room air
The End