Lect. 12 Temperature Control:

Reading Asst.: Ch. 16 pp.677-706 (skim 665-676 – metabolic rate)

I. Energy use related to Body size

A. Metabolic Rate/Mass vs. Body size across phyla

1. **Met. Rate of course increases with size**
2. **But normalize by dividing by Mass and get inverse relationship**
3. **Large animals use less energy per gram body mass than small animals**

B. Some (but not all) of this due to Surface Area

1. **Small animal has larger surface to volume (S/V) ratio**
2. **So , e.g. much more difficult to maintain temperature than large animal**

II. Why is Temperature Important?

A. All chemical processes are temperature dependent

B. In particular, enzymatic actions are affected by temperature

C. At extreme temperatures

1. **Proteins (e.g. enzymes) denature**
2. **Ice crystals form and rupture membranes**
3. **Membranes lipids become less fluid (cold) or too liquid (heat)**

D. Respiratory pigments (e.g. Hb) reduce affinity to O_2 too low

E. Muscle contraction gets VERY slow

1. **Warm muscle contracts 3x faster than cold with NO LOSS of FORCE**
2. **Power = Force X DLength / Time**
3. **In cold time increases with no change in Force and DLength**
4. **So, Power decreases**

F. But at temperature extremes there are Great Niches for life

1. **Some extreme conditions are remarkable stories**
2. **Desert living animals**
3. **Fish living in Arctic below 0^oC**
4. **Moths that live only in winter**
5. **Humans live in all temperature extremes**
   a) **Utilize tools and exploited furs etc.**
   b) **Norse colonists settled Greenland 1000 years ago**

c) **Found Eskimos who had lived there for 6,000 years**

d) **Archeologists found bones etc. of animals that coexisted with Eskimos**

(1) ***Caribou***

(2) ***Moose***

(3) ***Bison***

(4) ***Bear***

(5) ***Hares***

(6) ***Seals***

(7) ***Walruses***

(8) ***Whales***

e) **So, you don't need down parka to survive extreme cold**

III. Sources of Heat

A. **Conduction: Transfer heat between objects that are in contact**

B. **Convection: Transfer of heat aided by movement of gas or liquid**

C. **Radiation: Transfer of heat via electromagnetic waves without direct contact**

D. **Evaporation: Dissipation of heat by using it to evaporate liquids (e.g. water)**

E. **Heat storage: Containment of heat in a mass – greatly affected by**

1. **Insulation**
2. **Surface to volume ratio**

IV. Classification of Temperature Control

A. **Homeotherm (warm blooded) – Keep temperature constant**

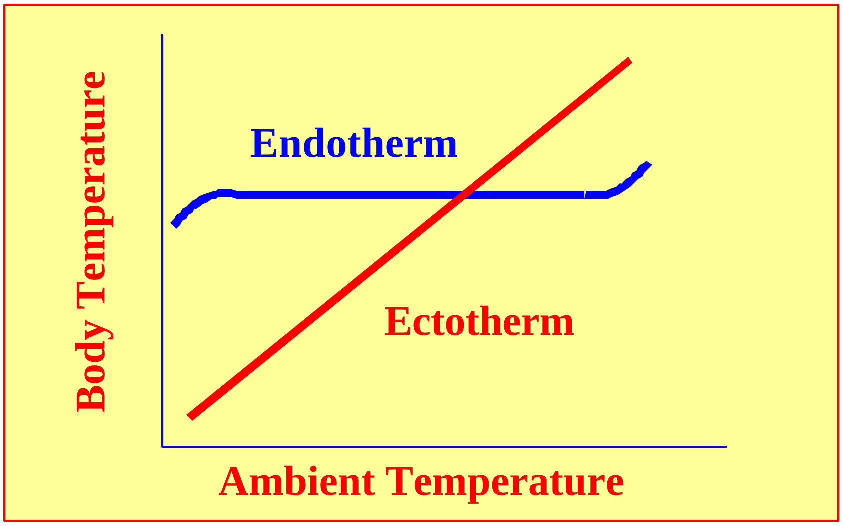
1. **But some lizards, fish and insects do good job of maintaining temperature**
2. **Use primarily behavioral methods**

B. **Poikilotherms (cold blooded) – Allow temperature to fluctuate**

1. **But many mammals allow temperature to fluctuate during day cycle**
2. **Camels let body temperature rise during day and drop at night**

C. **Ectotherm – Body temperature determined by outside factors**

1. **Environmental conditions**
2. **Not generated from inside body**
3. **Typically body temperature will match outside temperature**



D. **Endotherm - Generate heat from within body to maintain temperature**

1. Birds and mammals
2. Use metabolic heat to keep body temperature constant

E. **Heterotherm – Combination of Endothermy and Ectothermy**

1. Regional Heterotherm – Parts of body kept warm by endothermicy
2. Temporal Heterotherm – Body kept warm by endothermy certain times but allowed to drift toward T_b other times

V. Ectotherm

A. For small animals

1. Requires tremendous amount of energy to maintain temperature
2. Much easier to let temperature fluctuate

B. Aquatic Environment

1. Gill breathers VERY difficult to regulate body temperature
2. Water is HEAT SINK
   - a) Heat capacity of water ~3,000 x greater than air
   - b) Heat conduction ~10x faster than air
3. Gill breathers must have blood near water for long time
   - a) O_2 content of water low relative to air
   - b) Must allow time for transfer
   - c) Losing heat all the time O_2 is moving into gill
   - d) Increasing metabolic rate is losing proposition
     - *(1) Must increase O_2 intake*
     - *(2) Increase Blood flow to Gills*
     - *(3) Lose more heat than fish produces*

4. Skin has little insulation

- **a) No fur or feathers**
- **b) Little subcutaneous fat**

5. But large bodies of water do not fluctuate much

- **a) Even with ice on surface – warmer water below**
- **b) Farther down more constant temperature**

6. Strategies for survival

- **a) Behavior – move to warmer water**
  - ***(1) Go to deeper location***
  - ***(2) Migrate to warmer climate***

7. Regional heterotherms – Tuna and Mako Sharks

- **a) 1835 – Dr. John Davy voyage in tropics**
  - ***(1) Supplies supplemented with fish***
  - ***(2) Noted mammal-like red meat of skipjack tuna***
  - ***(3) Measure temperature***
  - ***(4) Warmer than water by 10^{o}C***
- **b) Dark muscle near backbone highly vascularized and contains O_2 transport pigments for long periods of contraction**
- **c) Warmest region within dark muscle**
- **d) Vascular system prevents heat loss through gills**
- **e) Counter-current for keeping heat in Core**
- **f) Rete Mirable (Wonderful Net) – Thermal barrier between dark muscle and gills**
- **g) Typical route: Gills → Dorsal aorta (in core) → Muscle → Heart → Gills**
- **h) HEAT GENERATED IN MUSCLE CONTRACTION LOST TO WATER IN GILLS**
- **i) Tuna: Gills → CUTANEOUS ARTERY → Rete → Muscle → Rete → Cutaneous Vein → Heart → Gills**
- **j) Rete – Many parallel small arteries and veins → massive counter current system**
- **k) Keeps heat in muscle**
- **l) Beyond rete cooler blood is in peripheral vessels**
- **m) No loss of heat to periphery either in conduction vessels or gills**
- **n) Mako shark same system – Convergent Evolution**
- **o) Another Rete in viscera (e.g. on surface of liver)**
- **p) Don't keep organs warm constantly**

q) **During periods of Digestion → Warm periods**

r) **May speed up digestive activity**

s) **Telemetry**

(1) ***Fish swimming into thermocline***

(2) ***Stomach temperature remains fairly constant as outside temperature drops ~ 10°C***

(3) ***Muscle remains constant as water temp drops ~ 5°C***

C. Terrestrial Environment

1. **Great variation in temperature**

a) **Day vs. Night**

b) **Sunny vs. Cloudy (or Shady)**

c) **Surface vs. Underground**

d) **Seasonal changes**

2. **Many ectotherms go along with temp – Cricket chirping**

3. **Behavior to regulate temperature**

a) **Curling up**

b) **Moving to warmer or colder areas**

c) **Adjust active time to Time of Day**

d) **Migrate (e.g. Monarch Butterflies)**

e) **Create favorable environment – (e.g. termites create mounds controlled air circulation for "air conditioning"**

f) **Basking in sun**

4. **Physiological processes to slow movement of heat into or out of body – Vascular changes**

a) **Galapagos Marine Iguana**

b) **Basking to warm Quickly: Sits on rock in sun – Higher body temperature coupled with**

(1) ***Higher heart rate***

(2) ***Vasodilation***

(3) ***Rapid circulation → Quick warming***

c) **Slow cooling: Jump into water – Cooler body temperature coupled with**

(1) ***Lower heart rate***

(2) ***Vasoconstriction***

(3) ***Rate of cooling slow***

5. **Heterothermic regulation**

a) **Insects must warm up flight muscles before flying**

(1) ***Shivering*****: *co-contraction of flight muscles***

(2) ***Generates heat***

(3) ***Must reach 30°C before muscle can contract fast enough to → flight***

b) **Most insects don't do well in cold**

(1) ***Typically die in fall***

(2) ***Eggs or pupae over-winter***

c) **Winter Moths – Reverse life cycle – late fall or winter die in spring**

(1) ***Caterpillers feed through spring***

(2) ***Pupae quiescent in summer***

(3) ***Adults live off sap of trees***

d) **Insulation – Thick pile made of scales**

(1) ***Remove scales and determine rate of cooling at typical wind speed for flight***

(2) ***Dipiliated moths cool down 2x faster than unshorn moths***

(3) ***Effective, but other moths have similar "coats"***

e) **Regional heating – Thorax warms up with little heat going to legs, wings, head or abdomen – Infrared image confirms**

f) **Air sacs behind ear (between thorax and abdomen) acts as thermal barrier**

g) **Counter-current Heat exchangers**

h) **Abdominal heat exchanger at junction between thorax and abdomen**

(1) ***Blood from thoracic hemocoel gives up heat to blood in dorsal vessel returning to thorax from abdomen***

(2) ***Countercurrent exchange***

i) **Thoracic heat exchanger – Dorsal vessel in thorax makes hairpin turn**

(1) ***Blood in descending arm give heat back to blood in ascending arm***

(2) ***So heat does not go into head where it can dissipate***

(3) ***Again countercurrent exchange***

j) **Bumblebees have best of both worlds – Temporal bypass**

(1) ***Can use exchangers***

(2) ***If cooling needed Separate blood flow at abdominal exchanger***

(3) ***Blood moves posteriorly during inhalation***

(4) ***Moves anteriorly during exhalation***

(5) ***Since blood not meeting at same time – No countercurrent***

6. **Endure temperature below freezing**

a) **Some have molecules that prevent ice crystal formation (e.g. glycerol)**

b) **Some have molecules that promote EXTRACELLULAR crystal formation**

(1) ***Need nuclei to seed ice crystal formation***

(2) ***Make crystals in extracellular fluid – no problem***

(3) ***Makes osmotic gradient to draw water out***

(4) ***Decreases ice crystal formation intracellularly***

c) **Arctic Ice fish – Super-cooling**

(1) ***Avoid nuclei for ice crystal formation***

(2) ***Live in sub-freezing temperatures with no ice crystals***

(3) ***Must avoid ANY contact with ice***

(4) ***Stay well below surface***

(5) ***Touch ice → RAPID CRYSTAL FORMATION AND DEATH***

7. **May just give up**

a) **Go into a suspended state**

(1) ***Pupal stages***

(2) ***Estivation – in low humidity snails enclose in shell and lungfish in cocoon***

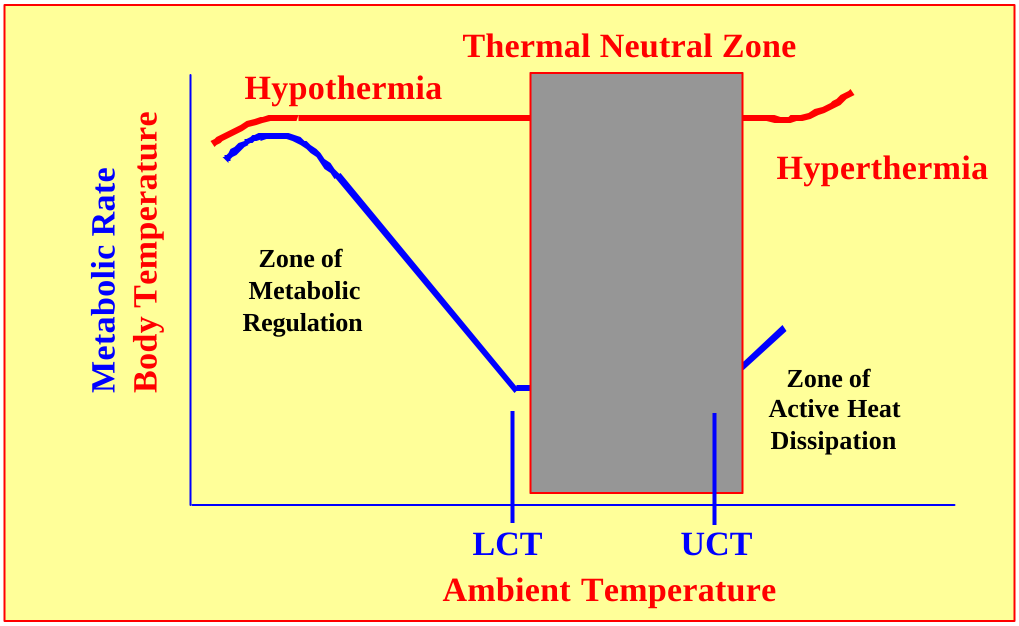
b) **Short life cycle: Lay eggs and die**

VI. Endotherms –

A. Energetically costly – But can stay active in broader range of temperature

1. **Metabolic rate 5-10x greater than ectotherm**
2. **Cannot solely rely on metabolic rate without eating constantly**
3. **Try to live in thermal zone where animal can rely on passive actions**

B. Thermal Neutral zone



1. Body temperature constant
2. $Q = C \times (T_b - T_a)$
3. Q = heat flow out of body
4. C = heat conductance
5. T_b = Body temperature
6. T_a = Ambient temperature
7. In TNZ Maintain Q by altering C
8. Increase C by:
   a) Directing blood to surface
   b) Slick down fur of feathers
9. Decrease C by:
   a) Fluffing fur and feathers
   b) Direct blood flow away from surface

C. Below LCT (lower critical temperature)

1. C is as low as it can go
2. T_a continues to drop
3. To maintain T_b MUST increase heat production
4. Zone of metabolic regulation - Thermogenesis
5. Shivering thermogenesis– Contract opposing muscles
   a) Little mechanical action
   b) Generates heat

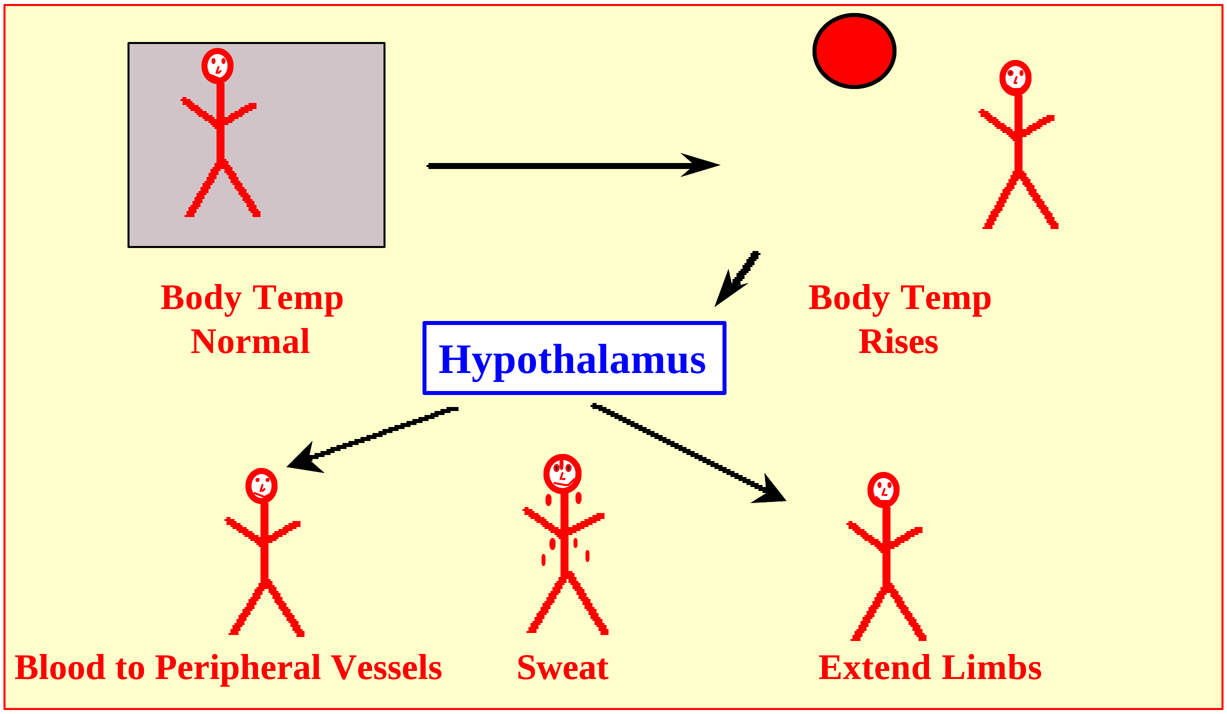
6. **Non-shivering thermogenesis – Enzymes activated to metabolize fat → heat**
7. **Brown fat – Small deposits in neck and shoulders**
    a) **Large amount of mitochondria → brown color**
    b) **Highly vascularized**
    c) **Metabolized in fat cells rather than broken down to fatty acids and transported to other cells for metabolism**
    d) **Rapid thermogenesis**
8. **All this is costly**
9. **Better to move LCT lower with passive properties**
    a) **Insulation**
    b) **Vascular effects**

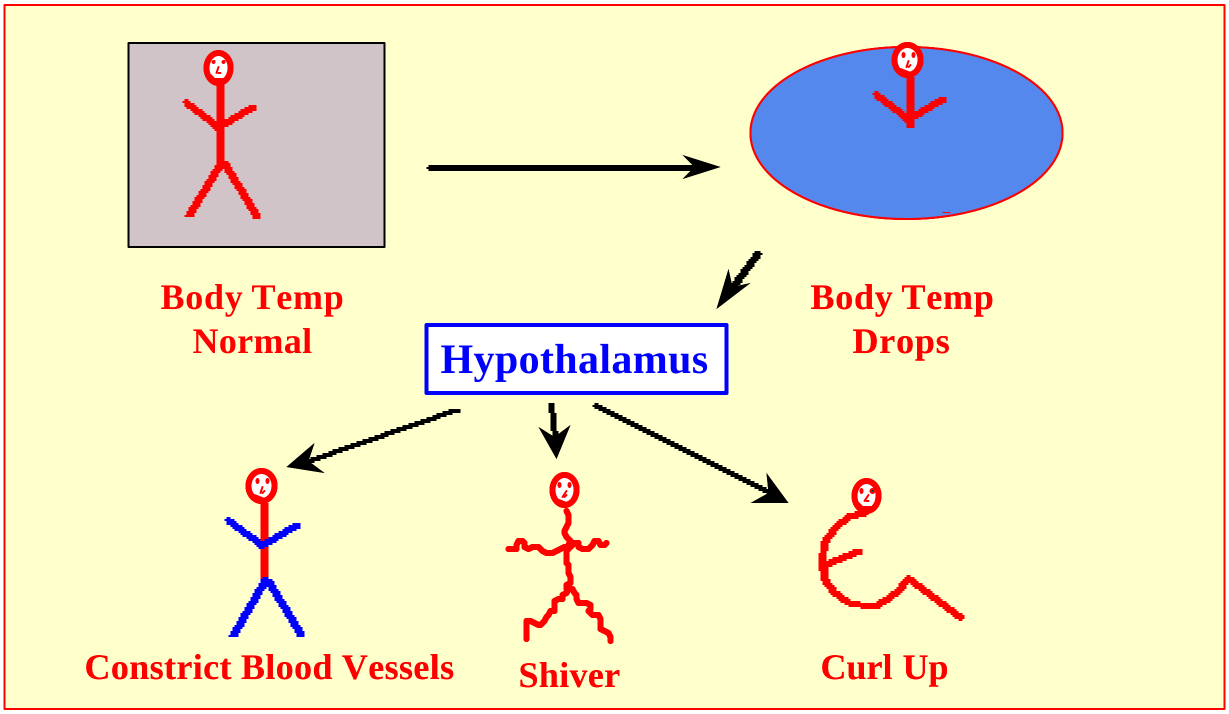
D. Above UCT (upper critical temperature)

1. **T_a approaches T_b**
2. **Gets hard to dissipate heat to environment regardless of how large C is**
3. **Must turn to Active Heat Loss – Evaporative cooling**
4. **Evaporation – 600 kcal/L of heat required to transform water from liquid to gas**
    a) **Sweating**
    b) **Panting**
    c) **Wetting skin or fur with saliva**
5. **Increase metabolic rate**
    a) **Due to direct temperature effect**
    b) **Also energy needs for Active heat loss**

E. Control – Hypothalamus Contains "Thermostat"

1. **Thermoreceptors**
    a) **Peripheral receptors in skin**
    b) **Central in deep body structures including hypothalamus itself**
    c) **Integrate in Hypothalamus**
    d) **Core receptors Much more effective than peripheral**
    e) **Peripheral → Feed-forward to avoid core temperature change.**





2. Output from hypothalamus to Effectors

a) Sympathetic nerves to:

(1) Sweat glands → Evaporative cooling

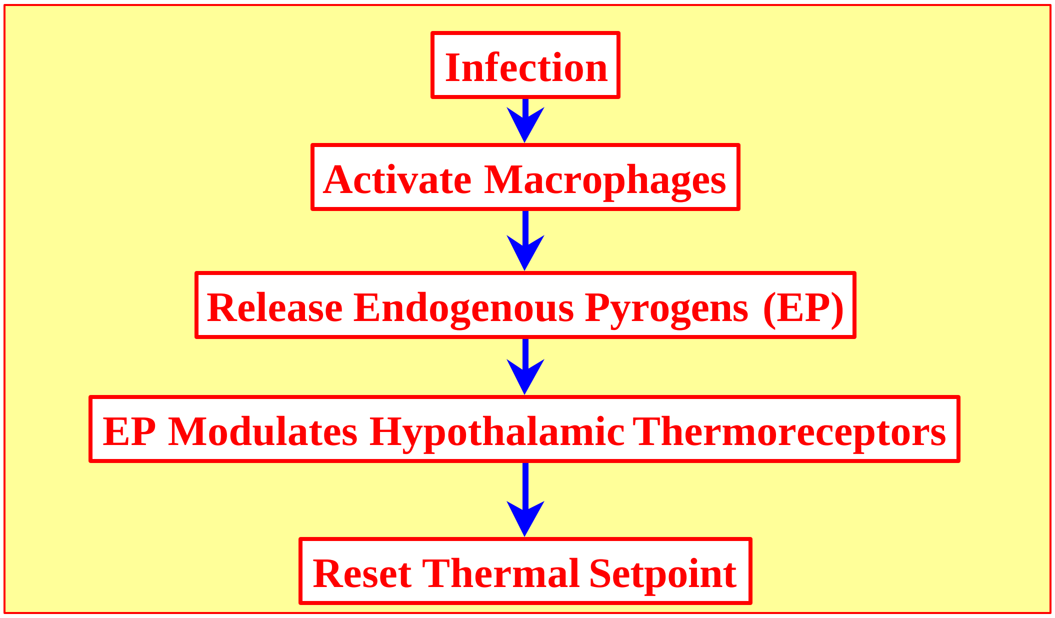
(2) Skin arterioles → bypass counter-current in arm → peripheral radiation

(3) Adrenal medulla → epinephrine → non-shivering thermogenesis

b) Skeletal Muscle activity – Shivering Thermogenesis

c) Some component of Thyroid hormone in infants (not in human adults)

3. Fever – Reset Setpoint



a) Infection activates monocytes and macrophages

b) Release messengers collectively called ENDOGENOUS PYROGENS (EP)

c) EP modulates thermoreceptors in Hypothalamus

d) Cells fire fewer A.P.s to input from integrating centers

e) Reset Setpoint – Cooling not initiated until higher body temperature

f) Mediated by Prostagandins

g) Aspirin blocks Prostaglandin synthesis

h) When fever breaks → Sweating and return to normal temperature

i) Modest fever beneficial – Speed up defense mechanisms to infection

j) Severe fever has strong deleterious effects on CNS

(1) Convulsions

(2) Brain damage

4. Heat Exhaustion – fainting due to hypotension brought on by:

a) Depletion of plasma volume secondary to sweating

b) Extreme dilation of Blood vessels

c) Body temperature only modestly elevated

d) Safety valve to avoid heat stroke

5. Heat Stroke

a) Complete breakdown of thermoregulatory mechanisms

b) Body temperature continues to rise

c) Leads to:

(1) collapse

(2) Delirium

(3) Seizures

(4) Coma

(5) Person no longer SWEATS

(6) Positive feedback loop (Higher temp → Higher metabolic rate → Higher body temperature)

VII. Adaptation to Extreme Temperatures

A. Trick in extreme conditions is to push UCT and LCT out

B. Want to use Passive adaptation as much as possible

C. Use active measures for transit regulation

D. Active measures CANNOT be used Chronically

E. Would take up too much energy – cannot eat enough

VIII. Extreme Heat – Desert (talked some in Water balance lectures)

A. Problem: Cannot use evaporation much (cannot waste water)

B. Camel DOES NOT store water in its hump or stomach

1. Hump – is Fat

a) Storage of fat in hump may help

b) On Dorsal side of body insulates against radiation heat from sun

c) No fat in other areas → radiation cooling from those "Heat windows"

d) Fur on Hump also → insulation

2. Stomach is typical ruminant stomach – several chambers

a) So-called "water sacs" do contain fluid

b) Is actually digestive juices

c) No more than other ruminants

d) But could → enough fluid to save a man in desert (although pretty disgusting)

C. Insulation

1. Loose fur insulates against heat

2. Not just against cold

3. People who live in desert wear lose, wool garments to insulate against heat

4. Shorn Camel → 60% more sweat than unshorn Camel

D. Allow temperature variation

1. Normal temp for mammal – 37°C (98.6°F)
2. Temperature drops to 34°C (93°F) during night
3. During Day Temperature rises to 41°C (105°F)
4. Never rises above 41°C – starts thermo-regulating then
5. Takes longer to get to point where thermo-regulation starts using energy
6. Only sweats during hottest part of day

E. Water Conservation

1. Monitor humidity in exhalent – Lower than expected given humidity from lungs
2. Save water from evaporation in exhalent
3. Nasal passage in nose has scroll-like passages – Increase surface area
4. TEMPORAL COUNTER-CURRENT EXCHANGER
   - a) Hygroscopic material – Dry mucous and cellular debri
   - b) Takes up humidity on exhaling – returns it on inhaling
   - c) Temporal counter-current
   - d) Model of Camel nose – Use Filter paper as hygroscopic material
   - e) Principle used for device → water conservation in patients with tracheotomy
     - *(1) Air not going through nose → dry trachea*
     - *(2) Funnel with hygroscopic material →*

F. Tolerate water loss and reclaim quickly

1. If man loses 12% of body water
   - a) Blood gets viscous
   - b) Cannot circulate well to periphery
   - c) No radiation cooling
   - d) Positive feedback → heat exhaustion and heat stroke
2. Camel can lose 25% of body weight and still function
3. Reclaim water quickly
   - a) Dehydrated camel looks emaciated
   - b) Drink 27 gallons in 10 minutes
   - c) Looks fine again

G. As with other animals route blood away from counter-currents to periphery

1. Radiation cooling from blood vessels in periphery

IX. Extreme Cold Conditions – Arctic Temperatures

A. Mechanisms available

1. Generation of body heat by metabolic burning of food
2. Use of insulation and other devices to retain body heat

B. Cannot rely on metabolic burning over long term

1. Take tropical animal to arctic – would need to generate 10x more heat to live
2. Would have to eat constantly
3. Polar bears don't sit around shivering all day
4. For long term rely upon passive devices

C. Fur (very thick) → great insulation

1. Arctic fox comfortable resting at –50°C
2. Tropical animal same size must increase metabolism at 20°C
3. Naked man starts shivering ~28°C

D. Subcutaneous Fat

1. Fur ok but has limitations
2. Subcutaneous fat serves as insulator
3. Can control circulation through fat or away from it
4. Shunt away from surface
5. Whales, walruses and hair seals very effective in cold
6. Walruses no fur, hair seals hair slicked down in water
7. Remain comfortable in water near freezing point due to fat

E. Cannot cover entire body with fur

1. Legs cannot function in locomotion with thick fur or fat
2. Use counter-currents to keep heat in trunk
   a) Whale flippers
   b) Bird and Mammal legs
   c) Without counter-current bird standing on ice would be froze to ice
3. In warm conditions route blood away from counter-current to periphery

F. Fat in lower extremities has lower melting point

1. More unsaturated double bonds → lower melting point
2. Neatsfoot oil from cattle feet makes good cold water lubricant

G. Burrow under snow

1. Smaller animals cannot carry enough fur for insulation

2. **Use insulation of snow**

H. Hibernation

1. **Dormancy during winter**
   a) **Slow wave sleep devoid of REM sleep**
   b) **Hypothalamus reset thermostat as much as 20°C below normal**
   c) **Thermoregulation not suspended just set lower**
   d) **Metabolic rate and blood flow reduced**
   e) **Drastic reduction of heart rate**
   f) **Come out periodically to eliminate wastes**
   g) **Takes 12-18 hrs to enter and 3 hours to arouse**
   h) **Rapid heating by brown fat and shivering during arousal**
   i) **Posture to conserve heat**
   j) **Very small mammals cannot hibernate**
      (1) Metabolic rate too high
      (2) Do go into daily torpor
   k) **Large mammals cannot hibernate**
      (1) Would take too long to raise and lower body temperature
      (2) Do not need to – can use body mass and insulation
      (3) Bears do Winter sleep – not hibernation
      (4) Drop in temperature sensitivity
      (5) Some drop in body temperature
      (6) But can arouse quickly
      (7) Recent observation – bears: no muscle atrophy

I. Acclimation

1. **Slowly alter physiology to adapt to cold**
2. **Alter enzymes to isozymes that function well at lower temperature**
3. **Alter membranes to lower melting point lipids**
   a) **More unsaturated C-C bonds**
   b) **More double bonds – fewer single bonds saturated with H**

X. In extreme – Give up fight with Thermodynamics

A. Entropy will ultimately win out in any system

B. Final Gambit:

1. **Package Genetic instructions up and make new individual**
2. **Leads us to Reproduction and Development of systems**