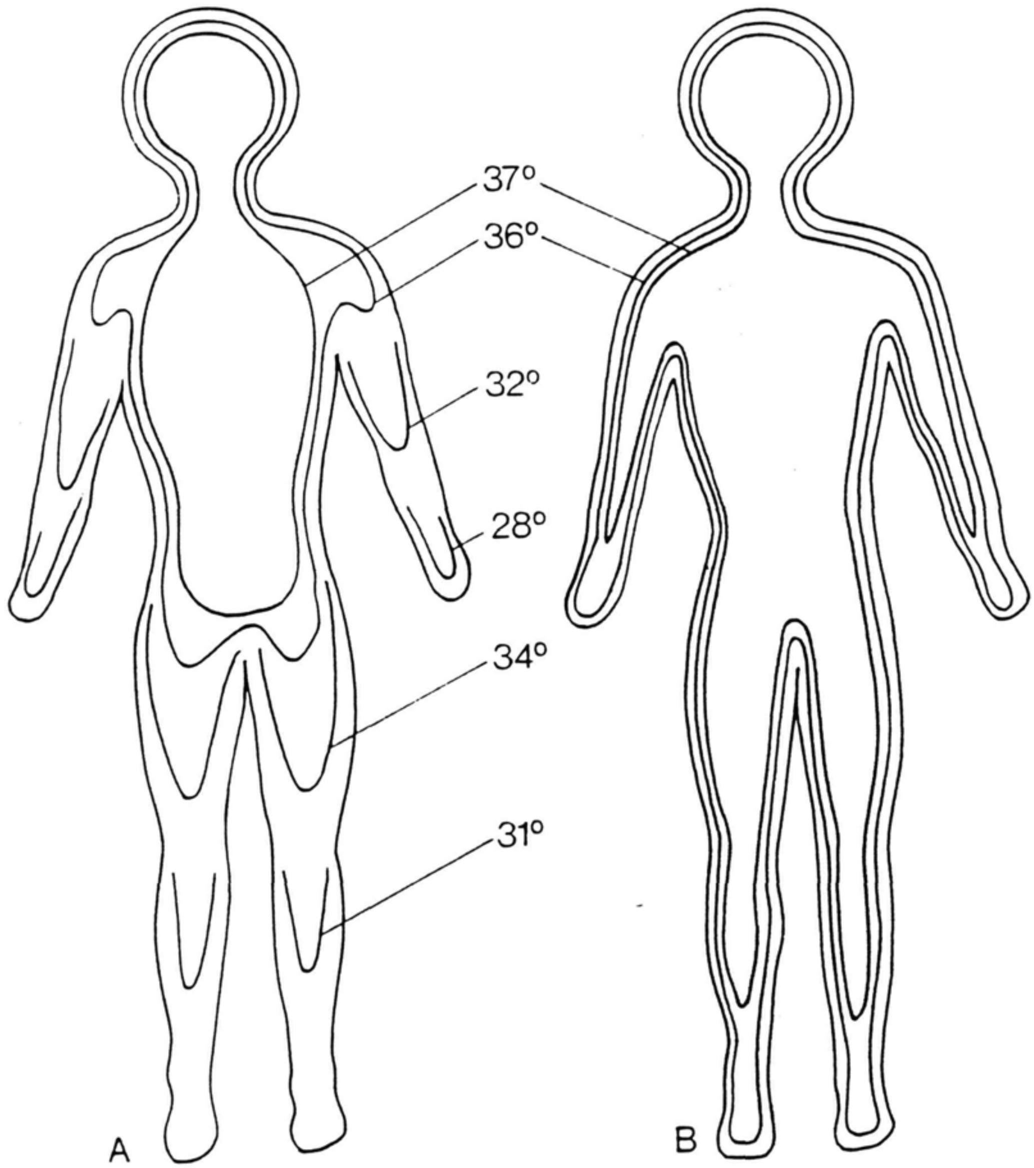
2. THE ENERGY HOUSEHOLD OF THE BODY

2.3. HEAT LOSSES OF THE BODY



The human body core temperature is constant around 37.1±1.0 ^{o}C
(degree Fahrenheit = degree Celsius · 1.8 + 32)

Constant body temperature guarantees nearly constant activity level

Extrem values of 28^{o}C and 45^{o} can be survived

To maintain constant temperature conditions within the body requires an internal temperature control system. The rate of temperature change is directly correlated to the rate of heat change within the body:

$$\frac{\Delta Q_{tot}}{\Delta t} = C\frac{\Delta T}{\Delta t}$$

C is the heat capacity of the human body, which derives from the specific heat c = 0.83 kcal/^{o}C kg. For a typical body mass of m=70 kg,

$$\Rightarrow \qquad C = c \cdot m = 58 \text{ kcal}/^{o}C$$

The heat change depends on the heat originated in the body (basal metabolic heat ΔQ_{bas} and the heat production while doing external work ΔQ_{ext}).

$$\Delta Q_{met}/\Delta t = \Delta Q_{bas}/\Delta t + \Delta Q_{ext}/\Delta t;$$

assuming that this is the only change in heat for the body:

$$\frac{\Delta Q_{tot}}{\Delta t} = \frac{\Delta Q_{met}}{\Delta t} = \frac{\Delta Q_{bas}}{\Delta t} + \frac{\Delta Q_{ext}}{\Delta t}$$

$$\frac{\Delta Q_{tot}}{\Delta t} = 58\left[\frac{kcal}{^{o}C}\right]\frac{\Delta T}{\Delta t}$$

The basal metabolic rate is:

$$\frac{\Delta Q_{bas}}{\Delta t} = 70 \left[\frac{kcal}{hr}\right] \equiv P_o$$

For heavy activities metabolic rate can increase up to a factor of $1 \leq \delta \leq 20$ (see tables)

$$\frac{\Delta Q_{met}}{\Delta t} = P_o + \frac{\Delta Q_{ext}}{\Delta t} = \delta \cdot P_o$$

if no heat losses occur and the operation of the temperature control system fails than the body temperature changes in accordance with:

$$C \cdot \frac{\Delta T}{\Delta t} = \delta \cdot P_o$$

$$\frac{\Delta T}{\Delta t} = \delta \cdot 70 \left[\frac{kcal}{hr}\right] \cdot \frac{1}{58} \left[\frac{^oC}{kcal}\right] = 1.2\delta \left[\frac{^oC}{hr}\right]$$

without heat losses and body temperature control the body temperature will increase between 1.2 and 24 ^oC per hour depending on the activity level. Therefore heat loss and temperature control mechanisms are necessary!

$$\frac{\Delta Q_{tot}}{\Delta t} = \frac{\Delta Q_{met}}{\Delta t} + \frac{\Delta Q_{cont}}{\Delta t} - \frac{\Delta Q_{loss}}{\Delta t}$$

Heat loss takes place by three (four) different mechanisms:

radiation $\frac{\Delta Q_{rad}}{\Delta t}$

convection $\frac{\Delta Q_{conv}}{\Delta t}$

evaporation $\frac{\Delta Q_{cont}}{\Delta t}$

conduction $\frac{\Delta Q_{cond}}{\Delta t}$

passive heat loss sources are radiation and convection from the exposed surface area of the body;
conduction is heat loss through covered surface parts of the body;
sweating is controlled by the internal temperature control system.

Heat loss due to radiation is described by:

$$\frac{\Delta Q_{rad}}{\Delta t} = \epsilon \cdot A_u \sigma (T_{skin}^4 - T_a^4)$$

T_a is the temperature of the outer environment, T_{skin} is the temperature of the human skin, ϵ is the emissivity of the skin, A_u is the exposed (uncovered) body area, and σ is the Stefan-Boltzmann constant.

$$T_{skin}^4 - T_a^4 = (T_{skin} - T_a) \cdot (T_{skin}^3 + T_{skin}^2 T_a + T_{skin} T_a^2 + T_a^3)$$

Approximation yields (within 23%):

$$T_{skin}^4 - T_a^4 = \approx 10^8 \cdot (T_{skin} - T_a)$$

$$\frac{\Delta Q_{rad}}{\Delta t} = \lambda_{rad} \cdot (T_{skin} - T_a)$$

$$\lambda_{rad} \approx 10^8 \epsilon \mathrm{A} \sigma \approx 12 \; \frac{kcal}{hr^o C}$$

$$\frac{\Delta Q_{rad}}{\Delta t} = 12 \frac{kcal}{hr^o C} \cdot (T_{skin} - T_a)$$

Radiative heat loss can be approximated by linear temperature relation!

This approximation is however only valid for:

$$0^o\mathrm{C} \leq \; T_a \; \leq 40^o\mathrm{C}$$

$$30^o\mathrm{C} \leq \; T_{skin} \; \leq 40^o\mathrm{C}$$

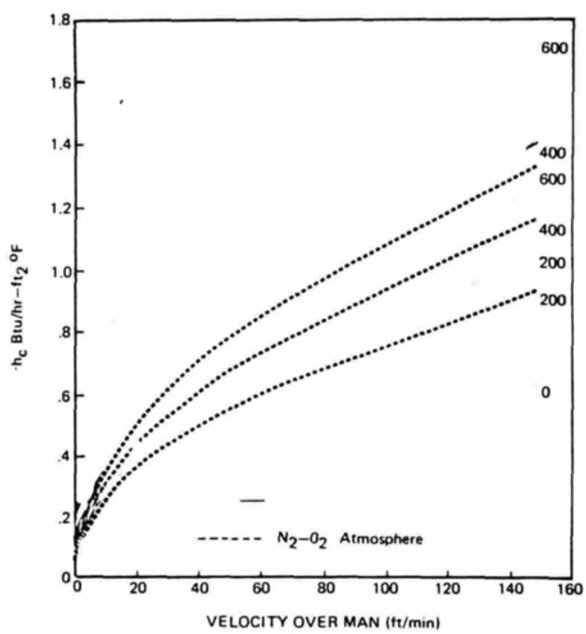
(good to 20% over this range of T_a and T_{skin})

Heat loss due to convection is described by:

$$\frac{\Delta Q_{conv}}{\Delta t} = K_{conv} \cdot A_u \cdot (T_{skin} - T_a)$$

A_u is the uncovered body area and K_{conv} is a factor which depends from the wind speed v in [m/s] .

$K_{conv} \approx 10.45 - v + 10\sqrt{v}\ kcal/hr^oC$ (valid between 2 m/s and 20 m/s)



for a nude body $A_u = A$

$\lambda_{conv} = K_{conv} \cdot A \approx 13\ \frac{kcal}{hr^oC}$

for a slight breeze of ≈ 0.1 m/s neglecting clothing of the body

$$\frac{\Delta Q_{conv}}{\Delta t} = 13 \frac{kcal}{hr^oC} \cdot (T_{skin} - T_a)$$

Total passive heat losses for a nude body in a light breeze due to radiative and convective processes are:

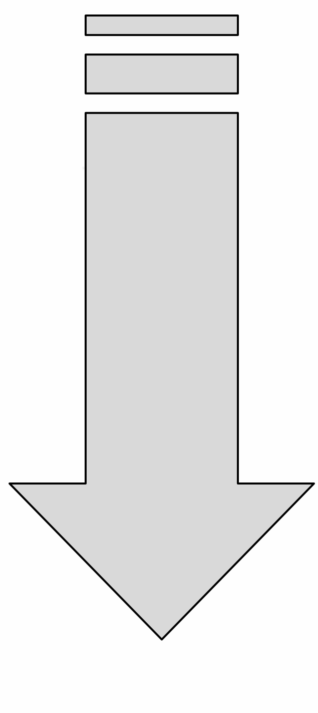
$$\frac{\Delta Q_{loss}}{\Delta t} \approx 25 \frac{kcal}{hr^{o}C} \cdot (T_{skin} - T_a)$$

Cooling effect increases with wind speed, therefore the effective temperature seems to be lower at high speeds of wind:

$\Rightarrow$ **wind chill factor**

$$\frac{\Delta Q_{conv}}{\Delta t} = K_{conv} \cdot A_u \cdot (T_{skin} - T_a)$$

as higher the speed of the wind as larger heat loss. Therefore the body experiences a heat loss which is equivalent to the one in a much colder outer environment.



Wind Chill Terms and Definitions

1. What is Wind Chill Temperature?
2. Can Wind Chill Impact my car's radiator or exposed water pipe?
3. What is Frostbite?
4. What is Hypothermia?

1. What is wind chill temperature?

A. The wind chill temperature is how cold people and animals feel when outside. Wind chill is based on the rate of heat loss from exposed skin caused by wind and cold. As the wind increases, it draws heat from the body, driving down skin temperature and eventually the internal body temperature. Therefore, the wind makes it FEEL much colder. If the temperature is 0 degrees Fahrenheit and the wind is blowing at 15 mph, the wind chill is -19 degrees Fahrenheit. At this wind chill temperature, exposed skin can freeze in 30 minutes.

2. Can wind chill impact my car's radiator or exposed water pipe?

A. The only effect wind chill has on inanimate objects, such as car radiators and water pipes, is to shorten the amount of time for the object to cool. The inanimate object will not cool below the actual air temperature. For example, if the temperature outside is -5 degrees Fahrenheit and the wind chill temperature is -31 degrees Fahrenheit, then your car's radiator will not drop lower than -5 degrees Fahrenheit.

3. What is FROSTBITE?

A. You have frostbite when your body tissue freezes. The most susceptible parts of the body are fingers, toes, ear lobes, or the tip of the nose. Symptoms include a loss of feeling in the extremity and a white or pale appearance. Get Medical attention immediately for frostbite. The area should be SLOWLY re-warmed.

4. What is HYPOTHERMIA?

A. Hypothermia occurs when body temperature falls below 95 degrees Fahrenheit. Determine this by taking your temperature. Warning signs include uncontrollable shivering, memory loss, disorientation, incoherence, slurred speech, drowsiness, and exhaustion. **Get medical attention immediately.** If you can't get help quickly, begin warming the body **SLOWLY**. Warm the body core first, **NOT** the extremities. Warming extremities first drives the cold blood to the heart and can cause the body temperature to drop further--which may lead to heart failure. Get the person into dry clothing and wrap in a warm blanket covering the head and neck. Do not give the person alcohol, drugs, coffee, or any HOT beverage or food. WARM broth and food is better. About 20% of cold related deaths occur in the home. Young children under the age of two and the elderly, those more than 60 years of age, are most susceptible to hypothermia. Hypothermia can set in over a period of time. Keep the thermostat above 69 degrees Fahrenheit, wear warm clothing, eat food for warmth, and drink plenty of water (or fluids other than alcohol) to keep hydrated. *NOTE: Alcohol will lower your body temperature.*

National Weather Service (NWS) Implements a New Wind Chill Temperature Index

Wind Chill Chart

Wind (mph) \ Temperature (°F) Calm	40	35	30	25	20	15	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45
5	36	31	25	19	13	7	1	-5	-11	-16	-22	-28	-34	-40	-46	-52	-57	-63
10	34	27	21	15	9	3	-4	-10	-16	-22	-28	-35	-41	-47	-53	-59	-66	-72
15	32	25	19	13	6	0	-7	-13	-19	-26	-32	-39	-45	-51	-58	-64	-71	-77
20	30	24	17	11	4	-2	-9	-15	-22	-29	-35	-42	-48	-55	-61	-68	-74	-81
25	29	23	16	9	3	-4	-11	-17	-24	-31	-37	-44	-51	-58	-64	-71	-78	-84
30	28	22	15	8	1	-5	-12	-19	-26	-33	-39	-46	-53	-60	-67	-73	-80	-87
35	28	21	14	7	0	-7	-14	-21	-27	-34	-41	-48	-55	-62	-69	-76	-82	-89
40	27	20	13	6	-1	-8	-15	-22	-29	-36	-43	-50	-57	-64	-71	-78	-84	-91
45	26	19	12	5	-2	-9	-16	-23	-30	-37	-44	-51	-58	-65	-72	-79	-86	-93
50	26	19	12	4	-3	-10	-17	-24	-31	-38	-45	-52	-60	-67	-74	-81	-88	-95
55	25	18	11	4	-3	-11	-18	-25	-32	-39	-46	-54	-61	-68	-75	-82	-89	-97
60	25	17	10	3	-4	-11	-19	-26	-33	-40	-48	-55	-62	-69	-76	-84	-91	-98

Frostbite Times: 30 minutes, 10 minutes, 5 minutes

$$\text{Wind Chill (°F)} = 35.74 + 0.6215T - 35.75(V^{0.16}) + 0.4275T(V^{0.16})$$

Where, T= Air Temperature (°F) V= Wind Speed (mph)

Effective 11/01/01

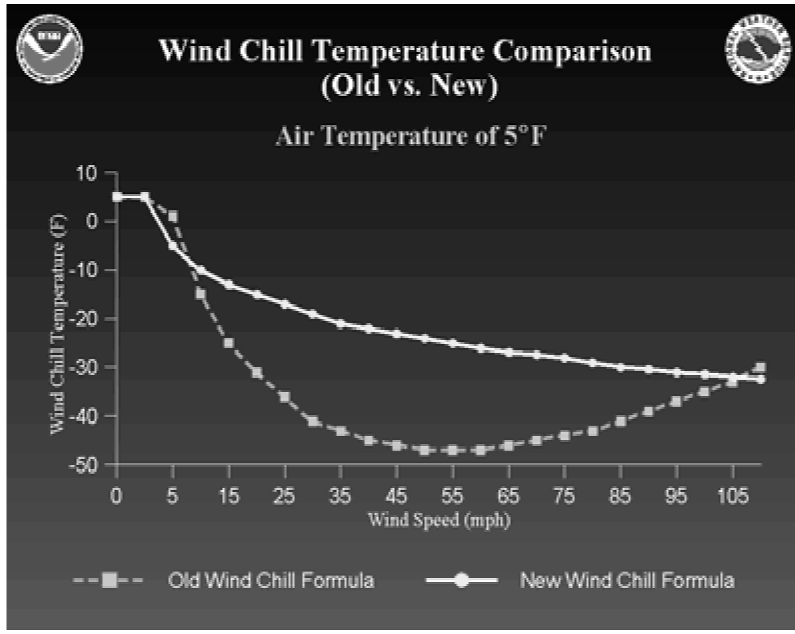
On November 1, The NWS implemented a replacement Wind Chill Temperature (WCT) index for the 2001/2002 winter season. The change improves upon the current WCT Index used by the NWS and the Meteorological Services of Canada, currently based on the 1945 Siple and Passel Index.

For more than a year, NWS and MSC have discussed updating the WCT. During the fall of 2000, the Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM) formed a group consisting of several Federal agencies, MSC, the academic community (Indiana University-Purdue University in Indianapolis (IUPUI), University of Delaware and University of Missouri), and the International Society of Biometeorology to evaluate and improve the wind chill formula. The group, chaired by the NWS, is called the Joint Action Group for temperature Indices (JAG/TI). JAG/TI's goal is to upgrade and standardize the index for temperature extremes internationally (e.g. Wind Chill Index).

After the October 2000 and February 2001 meetings, the JAG/TI reached agreement on a new wind chill formula, discussed a process for scientific verifications of the new formula, and developed plans for implementation of the new formula. The new WCT index was presented at the JAG/ TI meeting in Toronto, Canada on August 2, 2001.

The new formula uses advances in science, technology, and computer modeling to provide a more accurate, understandable, and useful formula for calculating the dangers from winter winds and freezing temperatures.

Clinical trials were conducted at the Defense and Civil Institute of Environmental Medicine in Toronto, Canada, and the trial results were used to improve the accuracy of the new formula and determine frostbite threshold values.



Standardization of the WCT Index among the meteorological community provides an accurate and consistent measure to ensure public safety. The new wind chill formula is now being used in Canada and the United States.

Specifically, the new WCT index will:

- Use calculated wind speed at an average height of five feet (typical height of an adult human face) based on readings from the national standard height of 33 feet (typical height of an anemometer)
- Be based on a human face model
- Incorporates modern heat transfer theory (heat loss from the body to its surroundings, during cold and breezy/windy days)
- Lowers the calm wind threshold to 3 mph
- Use a consistent standard for skin tissue resistance
- Assume no impact from the sun (i.e., clear night sky).

In 2002, NWS may adjust the WCT for solar radiation for variety of conditions (sunny, partly sunny, cloudy).

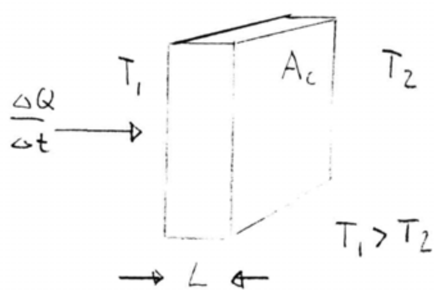
Note: *Wind Chill Temperature is only defined for temperatures at or below 50 degrees F and wind speeds above 3 mph.*

Heat loss due to conduction

Clothing has an insulating effect and reduces the energy loss by radiation and/or convection to the colder outer environment. However heat losses via conduction ΔQ_{cond} through the layers of cloth with thickness L can occur:

$$\frac{\Delta Q_{cond}}{\Delta t} = \frac{K_{cond} \cdot A_c}{L} \cdot (T_{skin} - T_a)$$

$$\frac{\Delta Q_{cond}}{\Delta t} = \frac{K_{cond} \cdot (A - A_u)}{L} \cdot (T_{skin} - T_a)$$



A_c is the covered body area, A is the total body area, and K_{cond} is a factor which describes the thermal conductivity through the clothing material:

$$K_{cond} \approx 0.04 \text{ - } 0.2\ kcal/(mhr^oC)$$

$I = L/K_{cond}$ is the insulation value of clothes in units:

$$1\ [\text{clo}] \equiv 0.18\ [^oCm^2hr/kcal]$$

Thick layer of clothing L or low thermal conductivity K_{cond} increases the insulation value I!

Recommended clothing to maintain suitable temperature conditions:

$I \approx 0.44$ Clo	in comfortable environment
$I \approx 0.1$ Clo	in hot environment
$I \approx 1.0$ Clo	in cold environment
$I \approx 10.0$ Clo	in arctic environment

$$\frac{\Delta Q_{cond}}{\Delta t} = \frac{A_c}{I} \cdot (T_{skin} - T_a)$$

This yields in a total heat loss due to radiative, convective, and conductive processes:

$$\frac{\Delta Q_{loss}}{\Delta t} \approx (25 \frac{kcal}{hr^oC} \cdot \frac{A_u}{A} + \frac{A_c}{I}) \cdot (T_{skin} - T_a)$$

$$\frac{\Delta Q_{loss}}{\Delta t} \approx (25 \frac{kcal}{hr^oC} \cdot \frac{A - A_c}{A} + \frac{A_c}{I}) \cdot (T_{skin} - T_a)$$

effective approximation for heat loss parameter K:

$$K \approx (K_{rad} + K_{conv}) \cdot (A - A_c) + \frac{A_c}{I}$$

large covered areas A_c and large insulation values I reduce the effective heat losses!

Consider **human body with heat input from metabolism and heat loss only by radiative and convective processes**

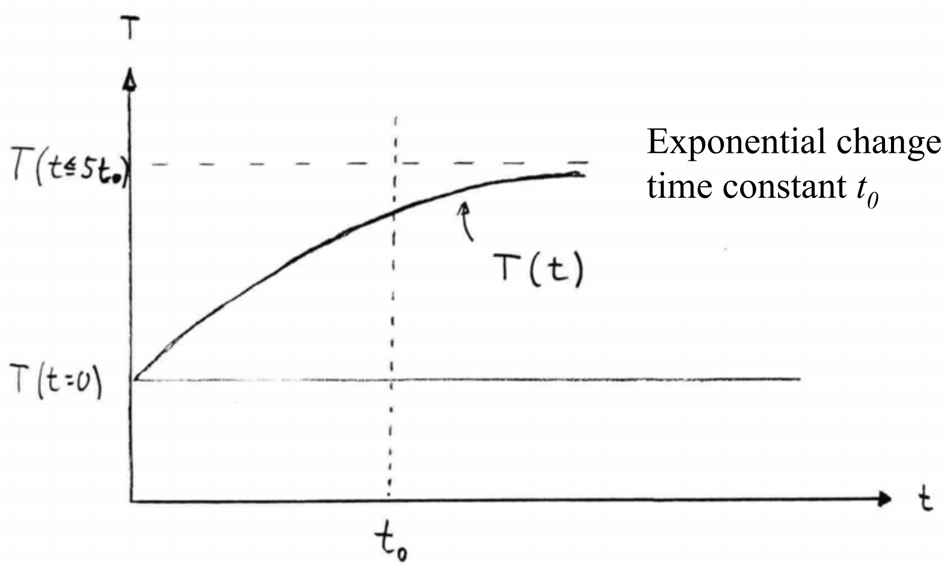
$$C\frac{\Delta T}{\Delta t} = \frac{\Delta Q_{met}}{\Delta t} - \lambda \cdot (T_{skin} - T_a)$$

The differential equation for the temperature is thus

$$\frac{\Delta T}{\Delta t} = \frac{1}{C}\frac{\Delta Q_{met}}{\Delta t} - \frac{\lambda}{C} \cdot (T_{skin} - T_a)$$

Solving the differential equation shows that temperature changes occur Exponentially and are determined by the time constant $t_0 \equiv C/\lambda$

$$T_{skin}(t) = T_{skin}(t=0) \cdot e^{-t/t_o} + T_{skin}(t \approx 5t_o)(1 - e^{-t/t_o})$$



Exponential change with slow time constant t_0

for the human body with C=58 kcal/°C and $\lambda \approx 25$ kcal/hr
$\Rightarrow$ $t_o \approx 2.3$ hr

Without additional heat control system it takes the body more than 2.3 hours to adjust to temperature changes!

How must λ adjust to maintain body temperature during physical activities (additional heat generation)?

approximation: $T_{skin} \approx T_{body} \approx 37\ ^oC$

$$\frac{\Delta Q_{met}}{\Delta t} = \frac{\Delta Q_{loss}}{\Delta t}$$

$$\delta \cdot P_o = \lambda (T - T_a)$$

for a person to maintain a comfortable temperature requires for the metabolic activity factor δ:

$$\delta = \frac{\lambda}{P_o} \cdot (T - T_a)$$

with $\lambda = 25\ kcal/hr^oC$ and P_o=70 $kcal/hr$

$$\delta = \frac{(T - T_a)}{2.8^oC}$$

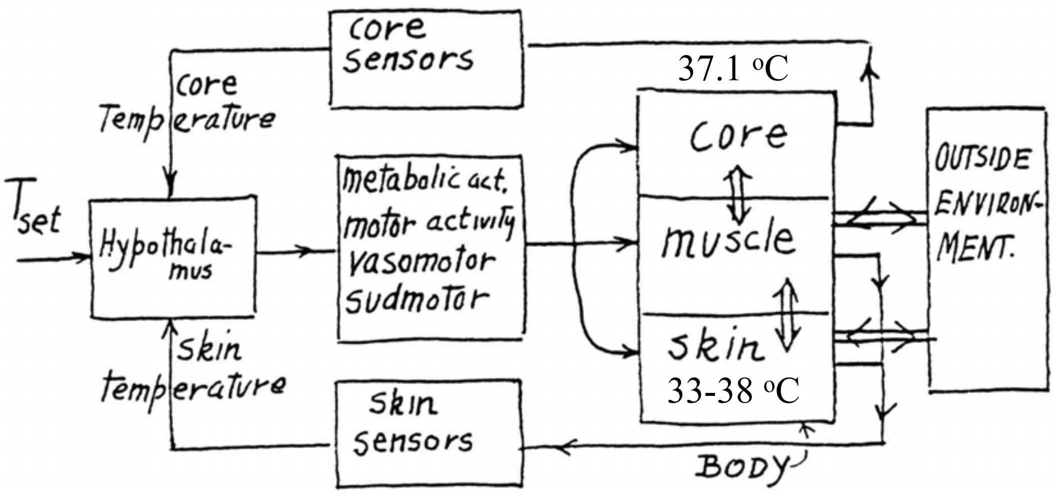
To feel comfortable without clothes at the beach at an air temperature of $\approx 21^oC$ (70^oF, the metabolic activity factor must be δ=6, the person must show at least 'moderate' activity (Catabolic rate ΔU/Δt≈400).

Without an internal temperature control system δ and λ must be always adjusted according to:

$$(T - T_a) = \frac{\delta P_o}{\lambda}$$

This requirement must be met by either adjusting the activity rate δP_o or the heat loss rate λ through the proper choice of clothes!

heat control system regulates heat sources and sinks and the timescale for temperature adjustments!



ELEMENTS IN THE HUMAN TEMPERATURE CONTROL SYSTEM

Using a simple approximation the body is characterized by core temperature T and skin temperature T_{skin}. Neurons transmit information about T to the control center in the hypothalamus. Core temperature is kept constant to $T \approx 37.1^oC$!

Skin temperature is measured by nerves which are sensitive to either hot or cold temperatures. The temperature plus the rate of change is transmitted to the hypothalamus. Skin temperature is allowed to vary over wide range between $\approx 33^oC$ and 38^oC.

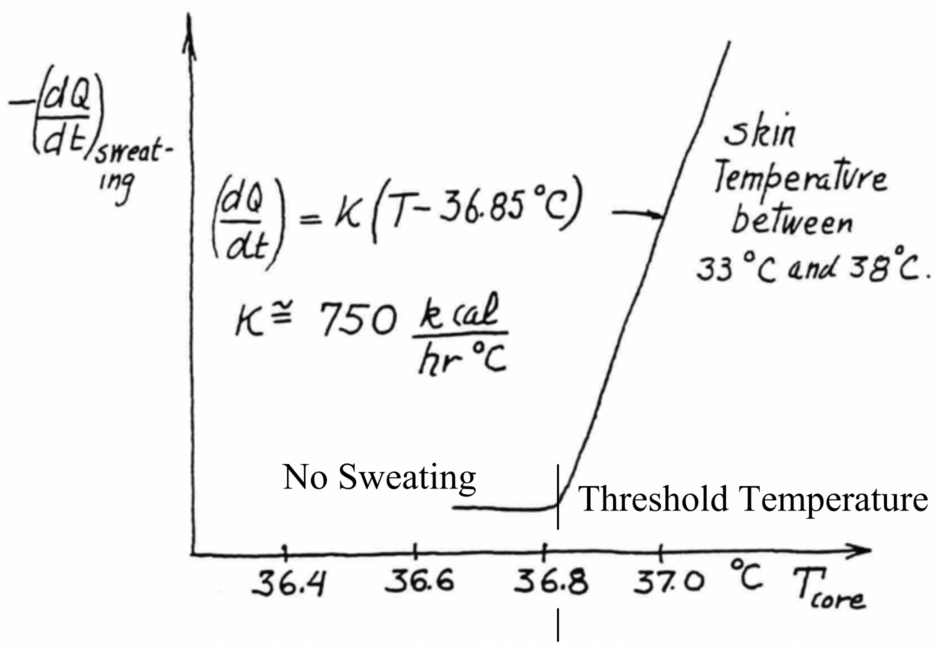
mechanism to increase body temperature

increase of internal metabolic activity by shivering
increase of blood transport, better heat conduction between different body parts

mechanism to decrease body temperature
Sweating, heat loss through evaporation (up to one l/hr)
latent heat of sweat ≈ 580 kcal/l

⇒ maximal 580 kcal/hr can be removed at dry air conditions!

If air is humid the evaporation losses are limited by the ability of the Ambient air to remove sweat from skin



RATE OF HEAT LOSS DUE TO SWEATING AS A FUNCTION OF CORE TEMPERATURE.

Below a core temperature $T \approx 36.85°C$ there is no sweating. For $T \geq 36.85°C$ heat can be removed by sweating at a rate independent of the skin temperature:

$$\frac{\Delta Q_{cont}}{\Delta t} \propto (T - 36.85^oC)$$

This yields for the heat balance system of the body:

$$C \cdot \frac{\Delta T}{\Delta t} = \delta \cdot P_o + \frac{\Delta Q_{cont}}{\Delta t} - \lambda(T - T_a)$$

$$\frac{\Delta Q_{cont}}{\Delta t} = -K \cdot (T - 36.85^oC)$$

where $K = L_V[kcal/l] \cdot \epsilon_V[l/hr^oC] \approx 580\epsilon_V[kcal/hr^oC]$

This is based on a latent heat for sweat of 580 $kcal/l$ and an evaporation rate of $\epsilon_V = \Delta V_{sweat}/\Delta t$

The solution of this modified differential equation results in a reduced time constant

$$t_{cont} = t_o/(1+K/\lambda) \approx t_o/31 = 4.5 \text{ min}$$

The body response time to temperature changes is much faster due to the heat control system

Maintaining the body temperature during physical activities, $\Delta T/\Delta t \approx 0$ is now described by:

$$\frac{\Delta Q_{met}}{\Delta t} = \frac{\Delta Q_{loss}}{\Delta t} - \frac{\Delta Q_{cont}}{\Delta t}$$

$$\delta \cdot P_o = \lambda(T - T_a) + K \cdot (T - 36.85^oC)$$

This changes now the activity factor δ to maintain a comfortable body temperature

$$\delta = \frac{\lambda}{P_o} \cdot (T - T_a) + \frac{K}{P_o} \cdot (T - 36.85^oC)$$

with $\lambda = 25\ kcal/hr^oC$, P_o=70 $kcal/hr$, and K=580$\cdot\epsilon_V kcal/hr^oC$

$$\delta = \frac{(T - T_a)}{2.8^oC} + \frac{\epsilon_V \cdot (T - 36.85^oC)}{0.12^oC}$$

This yields for a body temperature of $T \approx 37^oK$

$$\delta = \frac{(37 - T_a)}{2.8^oC} + 1.25 \cdot \epsilon_V$$

The normal daily evaporation rate is $\epsilon_V \approx 12\ ml/hr$, therefore to avoid heavy sweating an activity factor of $\delta \leq 13.2 - 0.36\ T_a$ has to be maintained!

For any outside temperature T_a a metabolic rate of $\delta \cdot P_o$ can be reached without heat regulation via evaporation

T_a	δ_{max}	$\delta \cdot P_o$
$[^oC]$		$[kcal/hr]$
9	10	700
23	5	350
31	2	140
34	1	70

At temperatures above 32^oC sweating takes always place

For a every activity factor δ and outside temperature T_a the evaporation rate ϵ_V be calculated.

$$\epsilon_V \approx \frac{\delta}{1.25} + \frac{T - T_a}{3.5^oC}$$

This yields $\epsilon_V \approx 0.8\delta$ - 11 $+0.3T_a$ $[l/hr]$

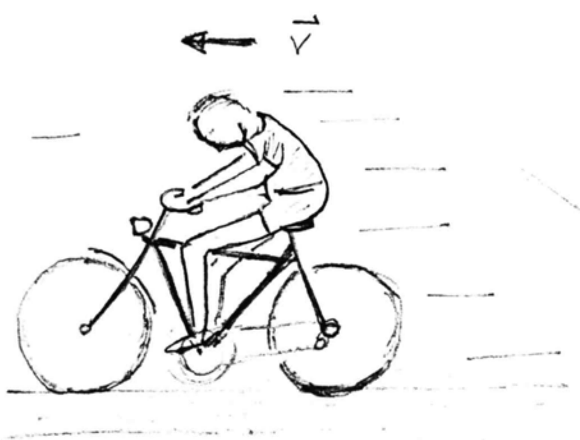
The evaporation rate is calculated for certain activity factors δ at different abient temperatures T_a

δ	T_a=26^oC	T_a=28^oC	T_a=30^oC	$\delta \cdot P_o$
	$[l/hr]$	$[l/hr]$	$[l/hr]$	$[kcal/hr]$
4	0	0.6	1.2	280
6	1.6	2.2	2.8	420
8	3.2	13	-	560

For high activity levels at high temperatures extreme values are required for the evaporation rate to maintain a constant body temperature.

EXAMPLE BICYCLE TOUR

Suppose you ride your bicycle at a warm summerday withT_a=28^oC along a country road with a velocity of v=30 km/hr. Because of the warm weather you wear thin biker cloth with an insulation value of only I ≈0.1 *clo*, the clothes cover only A ≈$0.3m^2$ of the body surface. Calculate your heat losses necessary to maintain a constant body temperature T=37^oC on the basis of a metabolic rate of $\Delta Q_{met}/\Delta_t = \delta \cdot P_o = 600\ kcal/hr$!



RADIATIVE LOSSES

$$\frac{\Delta Q_{rad}}{\Delta t} \approx 12[\frac{kcal}{hr^oC}] \cdot (T - T_a) = 108\frac{kcal}{hr}$$

CONVECTIVE LOSSES

$$\frac{\Delta Q_{conv}}{\Delta t} \approx (10.45 - v + 10\sqrt{v}[\frac{kcal}{hr^oC}] \cdot (T - T_a) = 31[\frac{kcal}{hr^oC}] \cdot (T - T_a) = 279\frac{kcal}{hr}$$

CONDUCTIVE LOSSES

$$\frac{\Delta Q_{conv}}{\Delta t} \approx \frac{A_c}{I}[\frac{kcal}{hr^oC}] \cdot (T - T_a) = 3[\frac{kcal}{hr^oC}] \cdot (T - T_a) = 27\frac{kcal}{hr}$$

TOTAL HEAT LOSSES

$$\frac{\Delta Q_{loss}}{\Delta t} \approx 108 + 315 + 27 = 450\frac{kcal}{hr}$$

To compensate the heat production duw to the metabolic rate additional cooling by evaporation is necessary

$$\frac{\Delta Q_{met}}{\Delta t} \approx 600\frac{kcal}{hr} = 450\frac{kcal}{hr} + \frac{\Delta Q_{cont}}{\Delta t}$$

$$600\frac{kcal}{hr} = 450\frac{kcal}{hr} + \epsilon_V L_V \cdot (T - 36.85)$$

with $L_V \approx 580 kcal/l$:

$$0.32\frac{l}{hr} = \epsilon_V \cdot (T - 36.85)$$

0.5cm

This yields an evaporation rate of:

$$\epsilon_V \approx 2.13 \; [l/hr]$$

Reasonable experience of efficient sweat rate with good cooling as the wind helps evaporating the moisture at the surface of the skin.

The biker approaches a steep hill, because of his larger work efforts the metabolic rate increases up to 800 $kcal/hr$ but the speed drops to a mere v=10 km/h. Only the convective loss rate is affected.

NEW CONVECTIVE LOSSES

$$\frac{\Delta Q_{conv}}{\Delta t} \approx (10.45-v+10\sqrt{v}[\frac{kcal}{hr^oC}]\cdot(T-T_a) = 24.4[\frac{kcal}{hr^oC}]\cdot(T-T_a) = 219\frac{kcal}{hr}$$

reduced speed $\Rightarrow$ less cooling!

$$800\frac{kcal}{hr} = 446\frac{kcal}{hr} + \epsilon_V L_V \cdot (T - 36.85)$$ higher metabolic rate!

This yields a considerably higher evaporation rate of:

$$\epsilon_V \approx 4.1\ [l/hr]$$

The sweat rate nearly doubled, cooling will be less effective as the reduced wind is less effective in drying the moist skin. (Well known experience!)

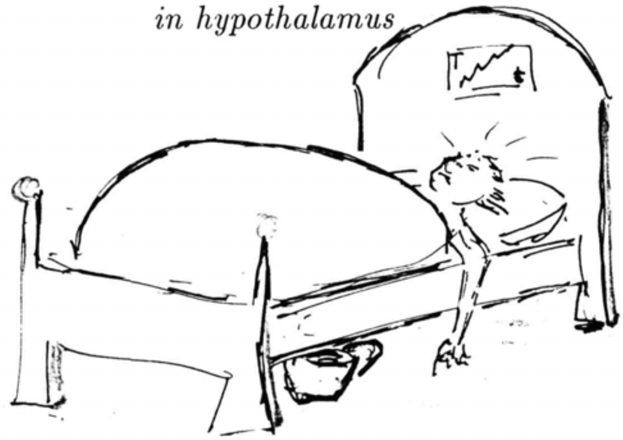
If the biker stops altogether to get a rest, convective cooling dissappears altogether, for a short time while the metabolic rate is still high (relaxation time of temperature regulation system) the only available heat loss is radiation (≈constant) and evaporation. This leads to a short term increase in evaporation:

$$\epsilon_V \approx 7.6\ [l/hr]$$

This is in agreement with everybodys observation when stopping after a hard bike ride.

Medical Implications of high Temperature Conditions

Fever results from infections (bacterial toxins $\equiv$ pyrogens) which alter the set point against which the core temperature of the body is measured in hypothalamus

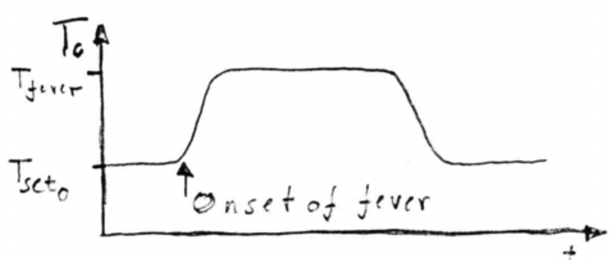


Onset of fever: $T_s et$ rises but core temperature T_c is below T_{set}

$\Rightarrow$ **patient feels cold**

Regulatory reactions of hypothalamus and patient

- restriction of blood flow to outer skin layers to reduce heat loss (skin looks pale and is cold)
- patient puts on blankets and additional clothing
- patient starts shivering (heat production by increase of metabolic heat production rate by internal muscle work)



After T_c rises to new set point temperature T_{set} "coldness" symptons disappear but skin temperature has also risen in response to increase of core temperature.

After infection subsides, T_{set} drops to normal $\Rightarrow$ patient feels to warm

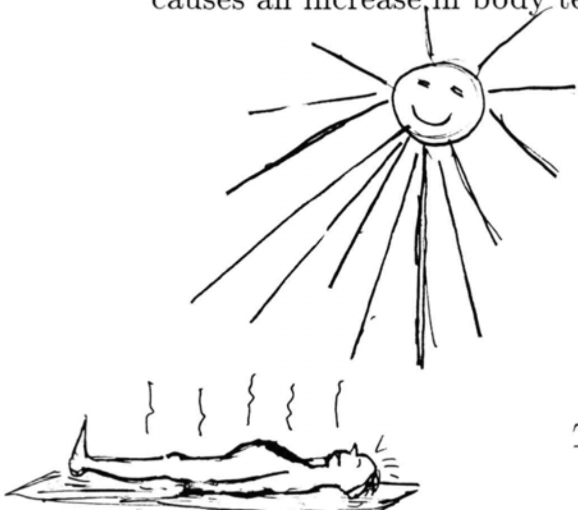
Regulatory reactions of hypothalamus and patient

- increase of blood flow to outer skin layers to enhance heat loss (skin looks flushed and is hot)
- patient throws off blankets and additional clothing
- patient starts sweating (additional heat loss)

Antipyretic drugs like *Aspirin* block pyrogens and keep set-point temperature at "normal"

Dangers of extreme outer Temperature Conditions

High summer temperatures or temperatures in a hot bath (sauna) causes an increase in body temperature due to heat absorption!



$$T \leq T_a$$

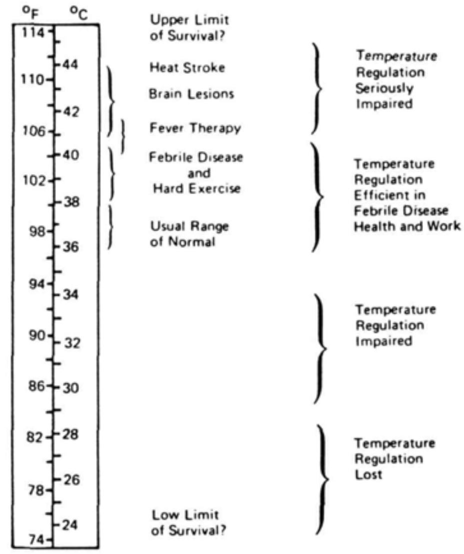
$$C \cdot \frac{\Delta T}{\Delta t} = \delta \cdot P_o + \frac{\Delta_{cont}}{\Delta t} \underbrace{- \lambda \cdot \underbrace{(T - T_a)}_{< 0}}_{\text{positive term}}$$

No heat loss except by sweating!!!
⇒ Danger of Heat Stroke!!!

Statistics

- Summer heat kills on average ≥ 1000 people/yr in the USA
- Heat stroke is second common cause of death among athletes in USA (Marathon running events) (high metabolic rate $\delta \cdot P_o$)
- Death in a Hot Tub: A.A. Bartlett & T. Braun, *Amer.J.of Physics* **51**, 127 (1983)

Development of Heat Stroke



1. body temperature rises → blood vessels dilate to transport heat to surface (in the vain attempt of cooling, further heating occurs!)
2. (watch for alcohol in the sauna: causes further dilation of blood vessels)
3. Blood pressure drops → blood flow through brain and heart is reduced
4. insufficient blood flow through brain (dizziness), intestines (nausea, vomiting), muscles (weakness), and heart (increase of pumping speed – heart rate)
5. complete breakdown of heat regulatory mechanism †

solution: keep your feet in cold water!