Introduction: review of ISO 7933

Predicted Heat Strain index (PHS) MODEL

Prevention

Expertise
Analysis
Observation
Screening

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Evaluation and Control of warm thermal working conditions
Barcelona June 14 & 15, 1999

ISO 7933 " interpretation of thermal stress using the Required Sweat Rate"

Main criticisms concerned:

- *The prediction of the skin temperature*
- *The influence of the clothing on convection, radiation and evaporation*
- *The combined effect of clothing and movements*
- *The increase of core temperature linked to the activity*
- *The prediction of the sweat rate in very humid conditions*
- *The limiting criteria and in particular the "alarm" and "danger" level*
- *The maximum water loss allowed.*

Predicted skin temperature (1/7)

ISO 7933 algorithm proposed by Mairiaux et al. (1986)

- *Based on a limited set of data for mainly nude subjects.*
- *Skin temperature decreases with the clothing*

⇒ *Use of the BIOMED database to check and extend the validity*

Predicted skin temperature (2/7)

Material and Methods

- **HEAT database (1113 files) containing minute by minute values of 10 parameters of stress and strain**
- **data points in steady state conditions were selected applying a set of selection criteria**
- **each observed t_{sk} is a weighted average of at least 4 local t_{sk}**
- **only data from male subjects**
- **final TSK database includes 1999 data points coming from 1399 conditions with 377 male subjects**
  - **➔largest database ever assembled**
- **separate analysis for nude (Icl ≤ 0.2 clo) and clothed (0.6 ≤ Icl ≤ 1.0) subjects (N=1212 and N=787)**
- **prediction model was derived using a multiple linear regression technique with re-sampling (non-parametric bootstrap)**

Predicted skin temperature (3/7)

Descriptive Results

Individual characteristics (N=377)

	Mean	SD	Minimum	Maximum
age (years)	28.1	10.3	19	59
body mass (kg)	74.3	9.2	52.0	104.6
height (cm)	179.9	6.5	162.0	194.0
Body surface (m^2)	1.93	0.13	1.54	2.25

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Predicted skin temperature (4/7)

Descriptive Results

Descriptive statistics of the primary parameters

	Nude Subjects (n=1212)			Clothed Subjects (n=778)		
Parameter	Mean	sd	Range	Mean	sd	Range
t_a, °C	35.0	8.4	20-55	31.8	9.7	15-55
t_r, °C	49.2	21.0	18-110	51.0	22.8	14-145
p_a, kPa	2.2	1.21	0.3-5.3	1.4	0.96	0.2-4.8
v_a, m/s	0.6	0.58	0.1-2.0	0.7	0.57	0.1-2.0
M, W	233	82	102-493	292	71	89-620
t_{sk}, °C	35.8	1.4	30.7-38.5	35.2	1.2	31.1-38.6
t_{re}, °C	37.5	0.4	36.1-38.9	37.5	0.4	36.3-39.4

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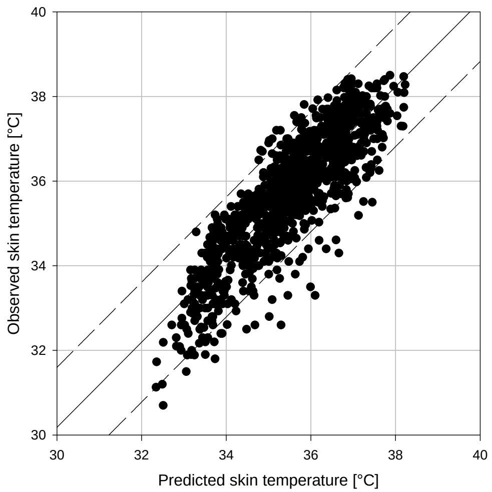
Predicted skin temperature (5/7)

Prediction model: nude subjects

$$t_{sk} = 7.19 + 0.064\ t_a + 0.061\ t_r + 0.198\ p_a - 0.348\ v_a + 0.616\ t_{re}$$



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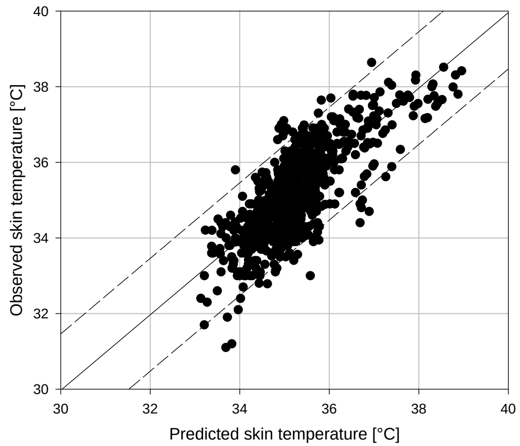
Predicted skin temperature (6/7)

Prediction model: clothed subjects

$$t_{sk} = 12.17+0.020\ t_a+0.044\ t_r+0.194\ p_a- 0.253\ v_a+0.003\ M+0.513\ t_{re}$$



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Predicted skin temperature (7/7)

Comparison with ISO 7933 prediction mode

correlation between observed and predicted skin temperatures

Prediction model	Nude subjects (n=1212)	Clothed subjects (n=787)	All subjects (n=1999)
Nude subjects	0.86	0.72	0.81
Clothed subjects	0.82	0.77	0.78
ISO 7933	0.75	0.56	0.69

Influence of the radiation protective clothing

When a reflective clothing is used

Correction factor F_{clR}

$$F_{clR} = (1 - A_p)\ 0.93 + A_p\ F_R$$

- **Reflection coefficient F_R**
- **Fraction A_p of the body surface covered by the protective clothing**
- **Reflection coefficient of normal clothing: 0.93**

Respiratory heat losses (1/3)

- ***Quite limited in hot climates, compared to neutral and cold climates***
- ***Often same order of magnitude than convective losses.***
- ***Heat storage determined by the difference between the required and predicted evaporation rates***
- ***Respiratory losses significant relative to this difference.***

Respiratory convective (C_{res}) heat losses (2/3)

Livingstone et al. (1994) :

$$C_{res} = c_p\ .\ V\ .\ (t_{ex} - t_{in})$$

where c_p is the specific heat of air.

$V = 0.076\ M$ (R = 0.992)

$t_{ex} = 28.6 + 0.115\ t_{in} + 0.641\ p_{a,in}$ (R = 0.979).

- **Metabolic rate (M, in watts)**
- **Ventilation rate (V, $l\ min^{-1}$)**
- **Temperatures of the expired air (t_{ex}, °C)**
- **Temperature of the inspired air (t_{in}, °C)**
- **Partial water vapour pressure of the inspired air ($p_{a,in}$, °C).**

$$C_{res} = 1.52\ 10^{-3}\ M\ (28.6 + 0.641\ p_{a,in} - 0.885\ t_{in})$$

Respiratory evaporative (E_{res}) heat losses (3/3)

Varene (1986)

$$E_{res} = 1.27\ 10^{-3}\ M\ (59.3 + 0.53\ t_{in} - 11.63\ p_{a,in})$$

Skin core temperature weighting (1/2)

- *ISO 7933 implicitly assumes a skin-core weighting of 0.3-0.7*
- *Regardless of the skin and core temperature*
- *Contradictory to the literature*

⇒ ***Must be revised.***

Mean body temperature (2/2)

Gagge and Nishi 1977; Stolwijk and Hardy 1966; Colin et al. 1971

$$t_b = \alpha\ t_{sk} + (1 - \alpha)\ t_{re}$$

- for vasoconstricted skin: $\alpha = 0.30$
- for vasodilated skin: $\alpha = 0.10$

Therefore

- $\alpha = 0.3$ for $t_{re} \leq 36.8°C$
- $\alpha = 0.1$ for $t_{re} \geq 39°C$
- α varies between 0.3 and 0.1 according to

$$\alpha = 0.3 - 0.09\ (t_{re} - 36.8)$$

Distribution of the heat storage in the body (1/3)

Distribution of heat storage between core and skin

⇒ ***Derive a valid estimate of the core temperature.***

Distribution of the heat storage in the body (2/3)

Assuming:

- at time (i-1)
  - skin temperature t_{sk0}
  - core temperature t_{co0}
  - skin-core weighting α_0
- during the last minute
  - heat stored dS_i
  - skin temperature at time i t_{sk}

Remain to be determined

- skin temperature at time i t_{co}
- skin-core weighting α

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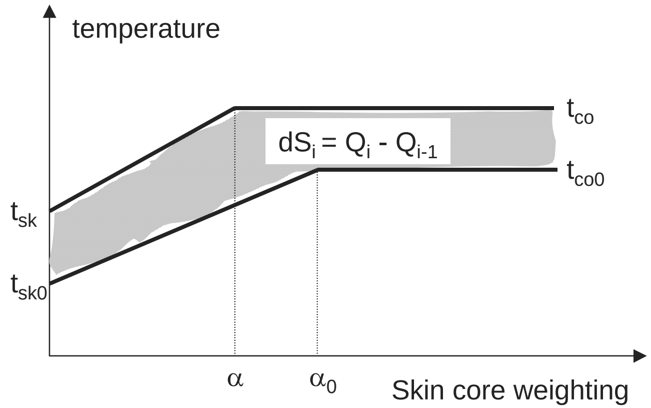
Distribution of the heat storage in the body (3/3)



$$t_{co} = \frac{1}{1 - \frac{\alpha}{2}} \left[\frac{dS_i}{c_p} + t_{co0} - \frac{t_{co0} - t_{sk0}}{2} \alpha_0 - t_{sk} \frac{\alpha}{2} \right]$$

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Prediction of the rectal temperature (1/3)

Rectal temperature remains, with heart rate, the easiest physiological parameter to record at the work place

⇒ The modified model must attempt to predict it directly.

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Prediction of t_{re} from the core temperature (2/3)

This core temperature t_{co} is the mean of

- the rectal temperature: characteristic of the muscle mass
- the oesophageal temperature: characteristic of the blood and influencing the hypothalamus.

The heat storage during a given unit of time results in an increase of

- the rectal temperature $dt_{re} = t_{re} - t_{re0}$
- the blood temperature $dt_{oe} = t_{oe} - t_{oe0}$

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Prediction of t_{re} from the core temperature (3/3)

Edwards et al.: $t_{oe} = a\,t_{re} + b\frac{dt_{re}}{dt} + c$

The analysis of the database

$$t_{oe} = 1.31 + 0.962\ t_{re} + 7.03\ dt_{re}$$

Assuming $t_{co} = (t_{oe} + t_{re}) / 2$

$$\Rightarrow \quad t_{re} = t_{re0} + \frac{2\,t_{co} - 1.962\,t_{re0} - 1.31}{9}$$

Increase in t_{co} associated with M (1/3)

Main objection to the ISO 7933:

- ***Does not take into account the normal increase in core temperature due to activity even in moderate and neutral climate.***

⇒ Include this in the prediction of the core temperature.

Increase in t_{co} associated with M (2/3)

Saltin (1966), in a neutral condition,

- $t_{cor} = 0.002M + 36.6$ (M in watts)
- t_{co} reaches t_{cor} with a time constant of about 10 minutes.

⇒ $t_{co} = t_{co0} \,.\, k + t_{cor} \,.\, (1-k)$

where: k = exp(-incr/10)

incr = the time increment, in minutes.

t_{co} = core temperature at time i

t_{co0} = core temperature at time (i-1)

Increase in t_{co} associated with M (3/3)

⇒ Heat storage associated with this increase:

$$dS_R = c_{sp}\,(t_{co} - t_{co0})\,(1-\alpha)$$

The body does not attempt to loose this heat storage

Therefore SW_{req} determined from $(E_{req} - dS_R)$

Total heat storage is $(E_{req} - E_p)$

Evolution of t_{sk} and SW with time (1/4)

Main limitation of the ISO 7933 standard:

- *Assume that a steady state is reached instantaneously.*
- *Impossible to predict the situation in case of intermittent exposure*
- *Heat accumulation assumed to remain the same during the WHOLE exposure*

⇒ Predict the sweat rate, the skin and rectal temperatures at any time, taking into consideration all of the past exposure.

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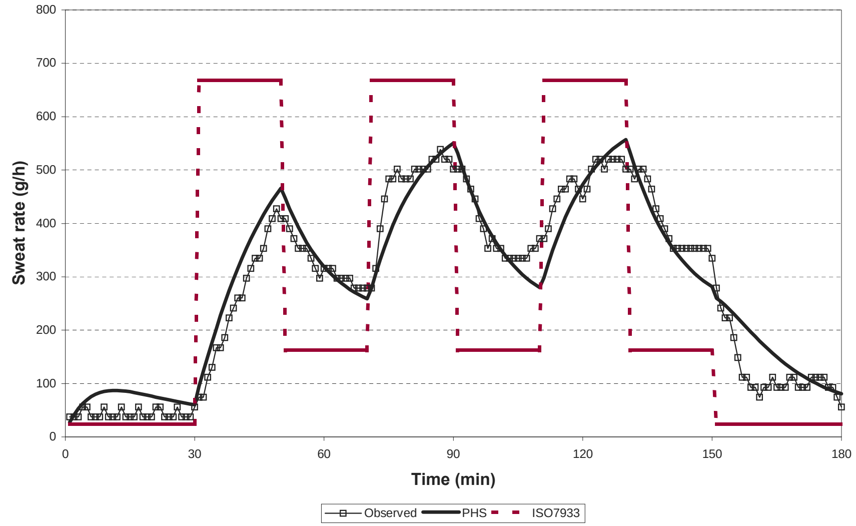
Exponential averaging for t_{sk} , SW (2/4)

Observed and predicted SW (using ISO 7933 and PHS) in a lab experiment with 3 sequences of work and climate.



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Exponential averaging for t_{sk} , SW (3/4)

According to the results of the ECSC research programme the skin temperature and the sweat rate tend to their equilibrium value as a first order system:

$$V(t) = V_0 + \Delta V \, [1 - \exp(- t/\tau)]$$

where

- **V(t)** is the value at time t
- **V_0** is the initial value
- **ΔV** is the increase of parameter V in the new condition, ($V_0 + \Delta V$) being therefore the new equilibrium value
- **t** is time
- **τ** is the time constant (in minutes).

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Exponential averaging for t_{sk} , SW (4/4)

Malchaire (1991)

$$V_i = V_{i-1} \, k + V_{max} \, (1- k)$$

where

- **V_i** is the value at time i
- **V_{i-1}** is the value at time (i-1), Δt min before
- **V_{max}** is the target value
- **τ** is the time constant (in minutes)
- **$k = \exp (- \Delta t / \tau)$**

Time constants equal to

- 3 minutes for the skin temperature
- 10 minutes for the sweat rate

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Evaporation efficiency (1/7)

⇒ ***Validation of the ISO 7933 expression for the computation of the evaporative efficiency as a function of skin wettedness***

Evaporation efficiency (2/7)

ISO 7933 assumes efficiency of 50% when $E_{req} > E_{max}$

- **Predicted evaporation rate limited logically to E_{max}**
- **But predicted sweat rate equal to $2.E_{max}$**

For more humid environments:

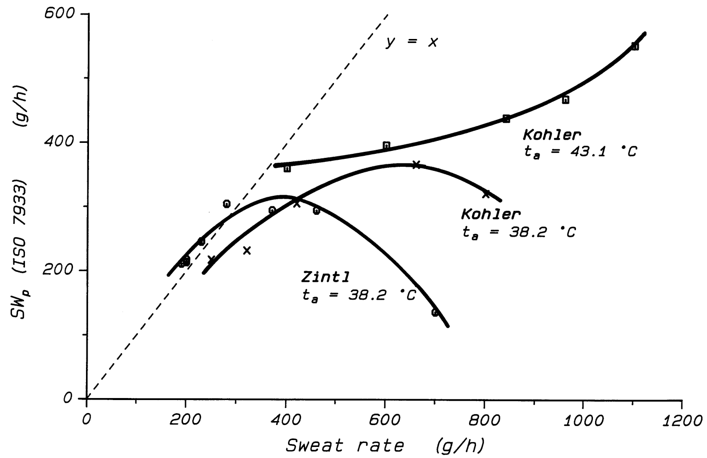
- **E_{max} is decreasing**
- **SW_p is decreasing**
- **A subject sweats less in extremely humid climates**

Contradicted by the literature

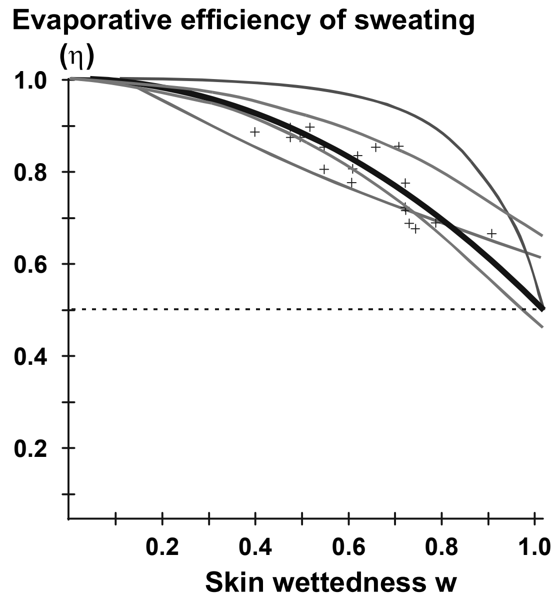
⇒ Revision of the evaporative efficiency prediction for very humid conditions

Evaporative efficiency of sweating (3/7)

Under very humid conditions



Evaporative efficiency of sweating (4/7)



$\eta = 1 - (e^{6.6\,(w - 1)})/2$ **(Vogt, 1982)**

$\eta = e^{0.6\,(0.12 - w)}$ **(Givoni, 1976)**

$\eta = 1 - w^2/2$ **(Hettinger et al., 1985)**

$\eta = 1 - w^2 / 1.85$ (men)

$\eta = 1 - w^2 / 2.95$ (women)

(Alber, Holmer, 1994)

Evaporative efficiency of sweating (5/7)

Under very humid conditions
In ISO 7933:

- **Maximum evaporation rate (E_{max}) decreases**
- **As the evaporation efficiency remains equal to 0.5 for wettedness > 1**
- **Predicted sweat rate decreases**

⇒ The subject would sweat less in an extremely humid condition

Evaporative efficiency of sweating (6/7)

Under very humid conditions

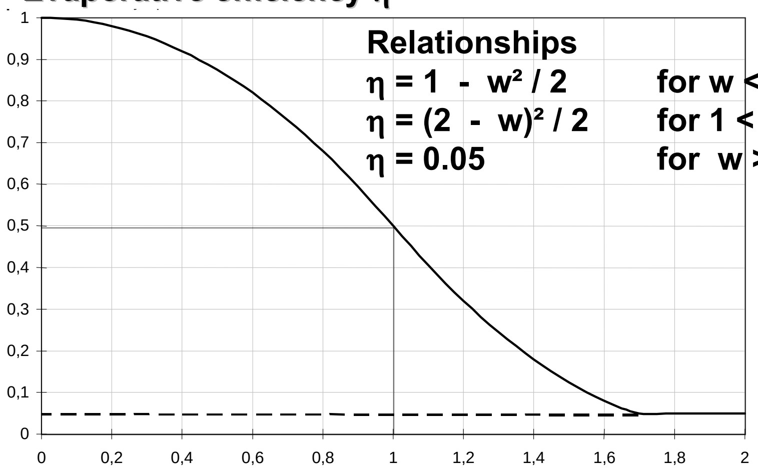
Candas (1980): the efficiency tends to 0 on a cylinder if the layer of water increases

⇒ Proposed relationship between skin wettedness and evaporation efficiency

Evaporative efficiency of sweating (7/7)

Under very humid conditions

Evaporative efficiency η



Skin wettedness w

Maximum wettedness (1/2)

ISO 7933 assumes w_{max} for unacclimatised subjects limited to 0.85

⇒ Confirmation.

w_{max} limit for non-acclimatised subjects (2/2)

Candas et al. (1979): 0.85

Alber-Wallerström and Holmér (1985): 0.83

⇒ confirm 0.85 as in ISO 7933.

Maximum sweat rate: SW_{max} (1/4)

ISO 7933 assumes constant values of maximum sweat rate for acclimatised and unacclimatised subjects

Values reduced by 2 when M < 65 W/m².

	Non-acclimatised		*Acclimatised*	
	Alarm	*Danger*	*Alarm*	*Danger*
SW_{max} (g/h)				
M < 65 W/m²	*260*	*390*	*520*	*780*
M ≥ 65 W/m²	*520*	*650*	*780*	*1040*
Maximum water loss (g)	*2600*	*3250*	*3900*	*5200*

- *Inconsistent results*

⇒ Revision

Maximum sweat rate: SW_{max} (2/4)

Gosselin (1947):

- **sitting person: SW = 4.2 weight + 142 g/h**
- **walking person: SW = 10.8 weight + 93 g/h**

For an average subject (75 kg):

- **sitting person: M = 105 watts**
- **walking person: M = 360 watts**

Spitzer et al. 1982: $M = M_{75}$ (1 + 0.01 (weight - 75))

⇒ SW = 3 (M - 59) in g/h with M in watts

Maximum sweat rate: SW_{max} (3/4)

Araki et al. (1979):

⇒ SW_{max} = 2.6 (M - 58) g/h

- **for M < 300 watts : 650 g/h (ISO 7933 "danger" level, ECSC project (Malchaire 1988))**
- **limited to 1000 g/h for unacclimatised subjects**

⇒ SW_{max} = M - 58 W/m² in the range from 250 and 400 W/m²

Maximum sweat rate: SW_{max} (4/4)

For acclimatised subjects:

- sweating in a given environment greater by a factor 2

Excluding the studies for which the maximum capacity was not reached:

- sweat rate increase by 25% (Havenith 1997)

Maximum dehydration and water loss (1/6)

ISO 7933 limit values questioned in the field, and particularly in mines

	Non-acclimatised		*Acclimatised*	
	Alarm	*Danger*	*Alarm*	*Danger*
SW_{max} (g/h)				
M < 65 W/m²	*260*	*390*	*520*	*780*
M ≥ 65 W/m²	*520*	*650*	*780*	*1040*
Maximum water loss (g)	*2600*	*3250*	*3900*	*5200*

⇒ Revision

Maximum dehydration and water loss (2/6)

- In very severe conditions, limit of core temperature at 38°C to exclude fainting and heat stroke
- Risk of heat cramps and dehydration in exposures of 4 to 8 hours, in less severe conditions

Maximum tolerable dehydration to be considered only in less severe conditions

Maximum dehydration and water loss (3/6)

**Szlyck (1989): threshold for thirst stimulation:
2% loss of body weight**

Candas et al. (1985): 3% dehydration induces a hypertonic hypovolemia associated with increased heart rate and depressed sweating sensitivity.

⇒ maximum dehydration in industry (not in the army or for sportsmen): 3% of body mass

⇒ sweat losses lower than 2000 g per shift cannot therefore lead to a significant risk of dehydration.

Maximum dehydration and water loss (4/6)

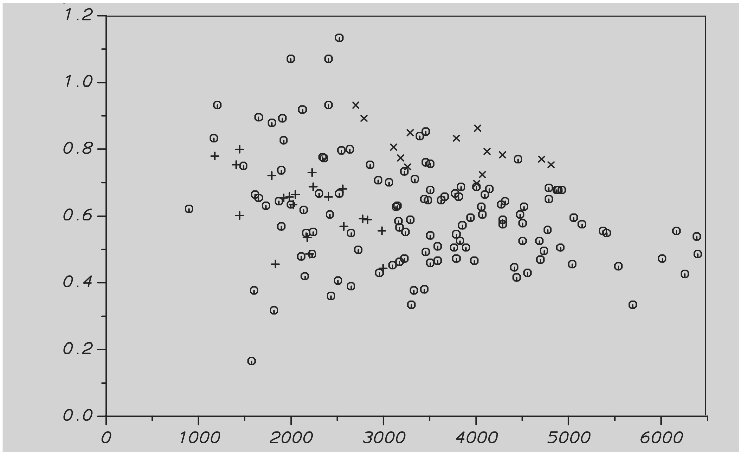
Adolph (1947): rehydration rate higher than 55% for sweat rates lower than 750 g/h

Kampmann et al.(1995): with exposure 4 to 8 hour

- average rehydration rate of 60%
- rehydration rate greater than 40% for 95% of the subjects

Maximum dehydration and water loss (5/6)

Rehydration rate



Total amount of sweat per shift (g)

Maximum dehydration and water loss (6/6)

⇒ **Maximum water loss**

- 7.5% of the body mass for an average subject
- 5% of the body mass for 95% of the working population

Limit criteria: ISO7933 (1/3)

ISO 7933 proposes limits for acclimatised and unacclimatised subjects at 2 levels of protection:

- *"alarm" level supposed to protect the entire population*
- *"danger" level supposed to protect most of the workers.*

Criteria too vague and too stringent.

- *Core temperature limit of 38°C offers a large degree of safety*

⇒ Change of criteria

Limit criteria: ISO7933 (2/3)

- *maximum water loss D_{max} (g), between 3.4 and 7% of an average body mass of 75 kg;*
- *a maximum heat storage of*
  - *50 Wh/m² at the "alarm" level, limit of the core temperature at 38°C;*
  - *60 Wh/m² at the "danger" level, limit of the core temperature at 38.2 °C.*

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Limit criteria: ISO7933 (3/3)

Acclimatised subjects

- perspire more
- more uniformly on their body surface
- earlier than non-acclimatised subjects
- loose less salt

⇒ lower heat storage
⇒ lower core temperature
⇒ lower cardiovascular constraint
⇒ able to endure a greater water loss.

Differences concerning w_{max}, SW_{max} and D_{max}

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Limit of internal temperature (1/12)

WHO document 1969:

- *Limit of 38°C commonly adopted and implicitly adopted in ISO 7933*

Document often quoted and altered

⇒ Revision of the basis and of the protection offered

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Limit of internal temperature (2/12)

WHO technical report N° 412 (1969): recommendations

- "It is inadvisable for deep body temperature to exceed 38°C in prolonged daily exposure to heavy work."
- "It is generally from the rectal temperature that is estimated the time at which it is necessary to interrupt a short duration exposure to intense heat in laboratory. In these closely controlled conditions, where the deep body temperature is continuously under surveillance, its increase is not generally considered to be a sufficient motive to stop the exposure until it does not reach values of the order of 39°C".

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Limit of internal temperature (3/12)

Alterations:

First NIOSH criteria (1972)

- "The WHO panel of experts recommended that a deep body temperature of 38°C should be considered as the limit of permissible exposure to work in heat".

Limit of internal temperature (4/12)

Second NIOSH criteria (1986)

- "it is inadvisable for deep body temperature to exceed 38°C in prolonged daily exposure to heavy work. In closely controlled conditions, the deep body temperature may be allowed to rise to 39°C"
- "If, ..., the t_{re} exceeds 38°C, the risk of heat casualties occurring increases. The 38°C t_{re}, therefore, has a modest safety margin which is required because of the degree of accuracy with which the actual environmental and metabolic heat load are assessed".

Limit of internal temperature (5/12)

Maximum rectal temperatures:

- 42° the maximum internal temperature to avoid any physiological sequels
- 39.2° "may rapidly lead to total disability in most men with excessive, often disturbing, physiological changes" Wyndham et al. (1965).

Maximum probabilities:

- for 42°: $< 10^{-6}$: <one heat stroke every 4 years among 1000 workers (250 days/year)
- for 39.2°: $< 10^{-3}$: <1 person at risk among 1000 shifts.

Limit of internal temperature (6/12)

Bases

Wyndham and Heyns (1973)

- standard deviation and skewness of distribution of t_{re} at high levels

Limit of internal temperature (7/12)

Wyndham's data

- for non acclimatised workers
  - 38.7°C for $p \leq 10^{-6}$ of reaching 42°C
  - 38.2°C for $p \leq 10^{-3}$ of reaching 39.2°C.
- for acclimatised workers
  - 39.4°C for $p \leq 10^{-6}$ of reaching 42°C
  - 38.3°C for $p \leq 10^{-3}$ of reaching 39.2°C.

Clearly, the 38.7 and 39.4°C are not defendable

38.3° and 38.2° are closed to 38°C (WHO document)

⇒ limit at 38°C

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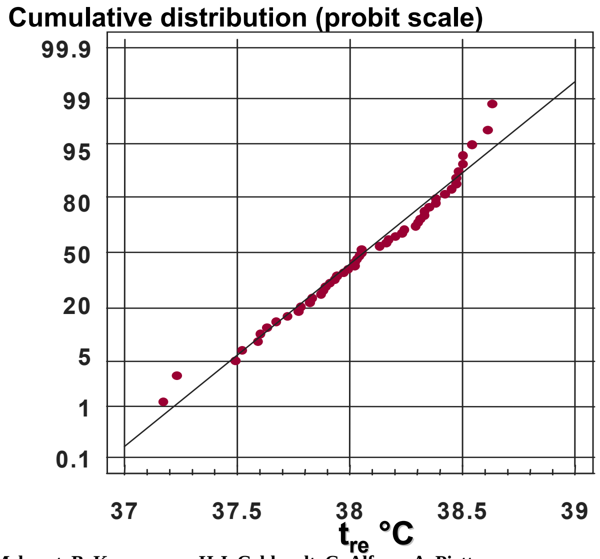
Limit of internal temperature (8/12)

Kampmann (1997): distribution of t_{re} after exposure to heat remarkably gaussian



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Limit of internal temperature (9/12)

⇒ Standard deviation at 38 °C: 0.29 °C

⇒ Probability of 39.2°C: 10^{-4}

⇒ Probability of 42.0°C: 10^{-7}

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Limit of internal temperature (10/12)

Remarks:

1. **Data concern rectal temperature, not core (blood) temperature.**

   Rectal temperature increases at the same rate than core temperature t_{co}

   ⇒ Results interpreted in terms of t_{co} instead of t_{re} with an additional slight safety factor.

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Limit of internal temperature (11/12)

Remarks:

2. Assumption that distribution of t_{re} around 38°C is the same for all conditions

   This is not the case: distribution changes with work type and the climate (narrower with warm humid).

   ⇒ Above figures offer an additional safety factor in these conditions

Limit of internal temperature (12/12)

Remarks:

3. Assumption that distribution of t_{re} around 38°C remains gaussian up to 42°C, that is, 13 standard deviations from the mean.

   Data suggest that the distribution is negatively skewed.

   The probabilities of reaching 39.2°C and 42°C would therefore be even lower

Limit of heat storage (1/2)

At rest in a comfortable environment (PMV = 0)

- Average values of t_{re} = 37°C and t_{sk} = 34°C

In hot conditions

- t_{re} equal to 38°C likely to correspond to t_{sk} = 36.8°C.

⇒ Increase in mean body temperature is 1.34°C.

⇒ Heat storage: 50 Wh/m^2 (ISO 7933, alarm level)

Limit of heat storage (2/2)

PHS model computes t_{co}:

1. prediction of t_{sk}
2. prediction of heat exchanges
3. prediction of heat storage
4. prediction of t_{re} taking into account the heat storage in the skin layer