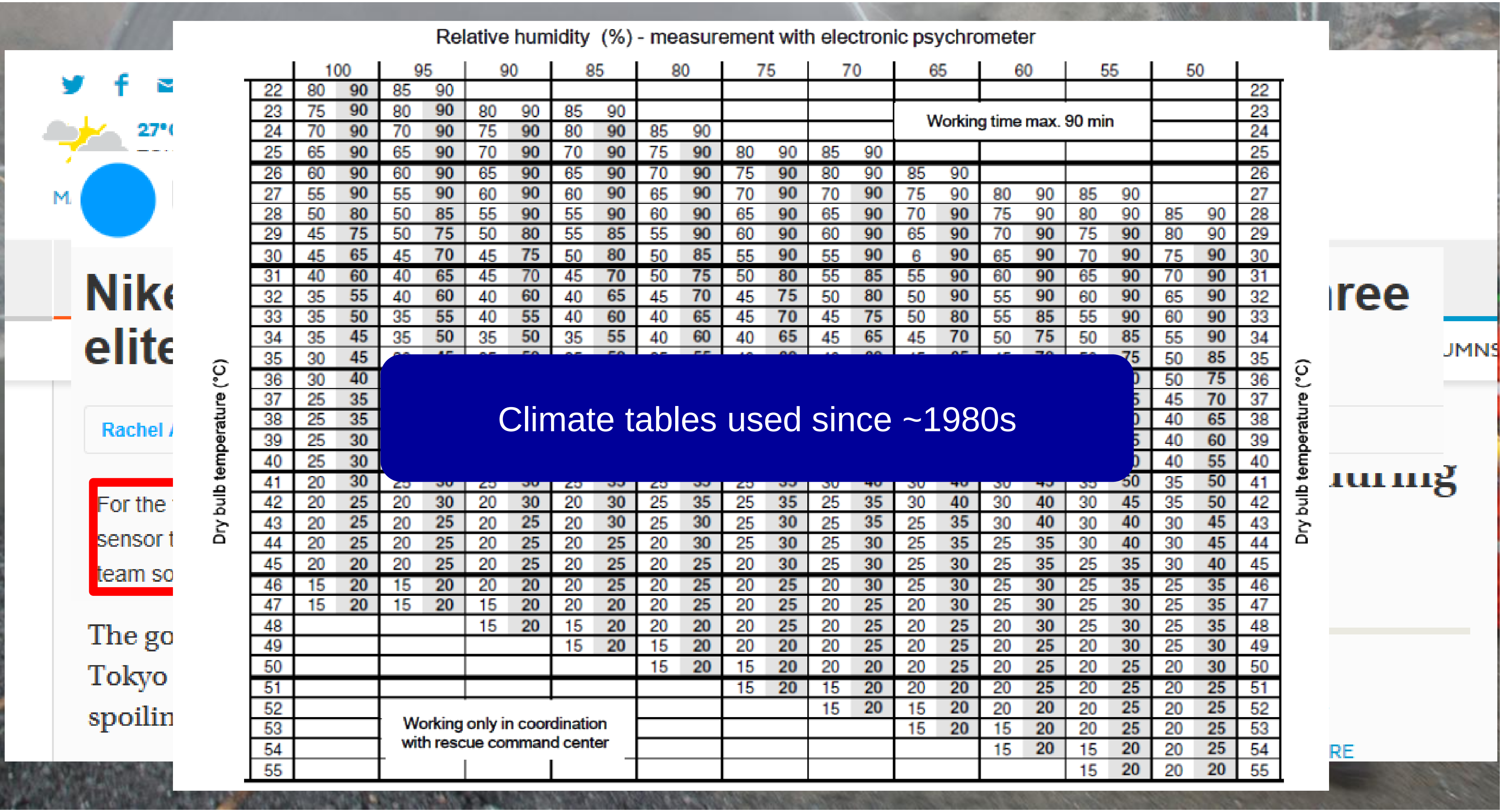
Core temperature sensing

New Technologies to accurately measure an essential parameter to improve Safety of Mines Rescuers

Новокузнецк, 09/05/2017, Dr. Marc-Florian Uth

Perfoming in severe environmental conditions



Relative humidity (%) - measurement with electronic psychrometer

Dry bulb temperature (°C)	100		95		90		85		80		75		70		65		60		55		50		Dry bulb temperature (°C)
22	80	90	85	90																			22
23	75	90	80	90	80	90	85	90							Working time max. 90 min								23
24	70	90	70	90	75	90	80	90	85	90													24
25	65	90	65	90	70	90	70	90	75	90	80	90	85	90									25
26	60	90	60	90	65	90	65	90	70	90	75	90	80	90	85	90							26
27	55	90	55	90	60	90	60	90	65	90	70	90	70	90	75	90	80	90	85	90			27
28	50	80	50	85	55	90	55	90	60	90	65	90	65	90	70	90	75	90	80	90	85	90	28
29	45	75	50	75	50	80	55	85	55	90	60	90	60	90	65	90	70	90	75	90	80	90	29
30	45	65	45	70	45	75	50	80	50	85	55	90	55	90	6	90	65	90	70	90	75	90	30
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32	35	55	40	60	40	60	40	65	45	70	45	75	50	80	50	90	55	90	60	90	65	90	32
33	35	50	35	55	40	55	40	60	40	65	45	70	45	75	50	80	55	85	55	90	60	90	33
34	35	45	35	50	35	50	35	55	40	60	40	65	45	65	45	70	50	75	50	85	55	90	34
35	30	45	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	75	50	85	35
36	30	40	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	50	75	36
37	25	35	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	45	70	37
38	25	35	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	40	65	38
39	25	30	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	40	60	39
40	25	30	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	40	55	40
41	20	30	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	50	35	50	41
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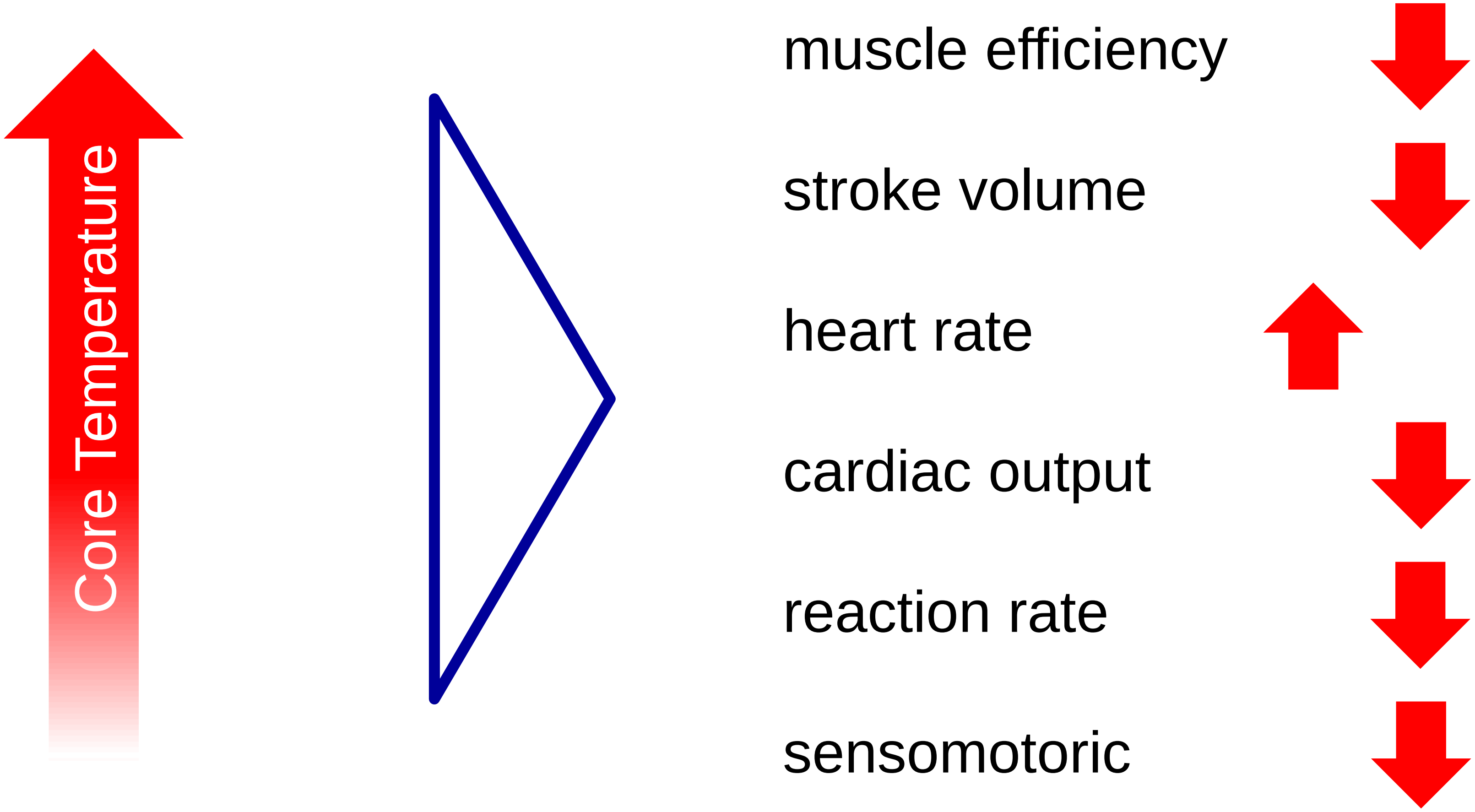
44	20	25	20	25	20	25	20	25	20	30	25	30	25	30	25	35	25	35	30	40	30	45	44
45	20	20	20	25	20	25	20	25	20	25	20	30	25	30	25	30	25	35	25	35	30	40	45
46	15	20	15	20	20	20	20	25	20	25	20	25	20	30	25	30	25	30	25	35	25	35	46
47	15	20	15	20	15	20	20	20	20	25	20	25	20	25	20	30	25	30	25	30	25	35	47
48					15	20	15	20	20	20	20	25	20	25	20	25	20	30	25	30	25	35	48
49							15	20	15	20	20	20	20	25	20	25	20	25	20	30	25	30	49
50									15	20	15	20	20	20	20	25	20	25	20	25	20	30	50
51											15	20	15	20	20	20	20	25	20	25	20	25	51
52			Working only in coordination with rescue command center										15	20	15	20	20	20	20	25	20	25	52
53															15	20	15	20	20	25	20	25	53
54																	15	20	15	20	20	25	54
55																			15	20	20	20	55

Climate tables used since ~1980s

Impact of increasing core temperature

on human physiology



Core Temperature

muscle efficiency ↓

stroke volume ↓

heart rate ↑

cardiac output ↓

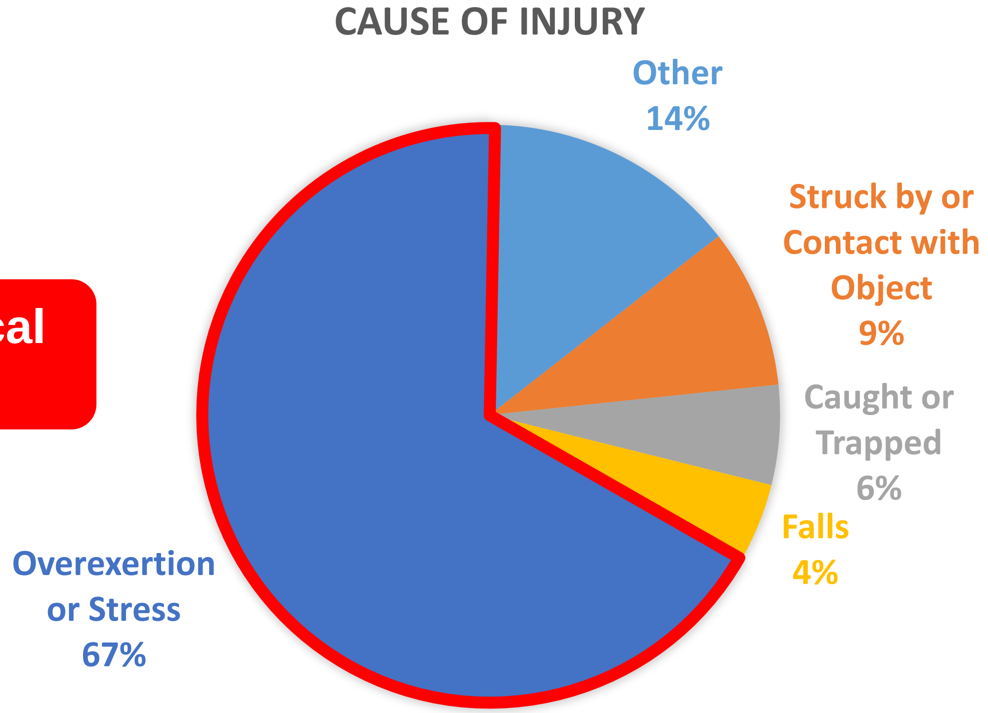
reaction rate ↓

sensomotoric ↓

Comparison to fire fighters

A relevant percentage of fire fighters come to death under mission due to physiological stress

physiological Stress



other

Firefighter Fatalities in the United States in 2015, U. S. Fire Administration
90 in total

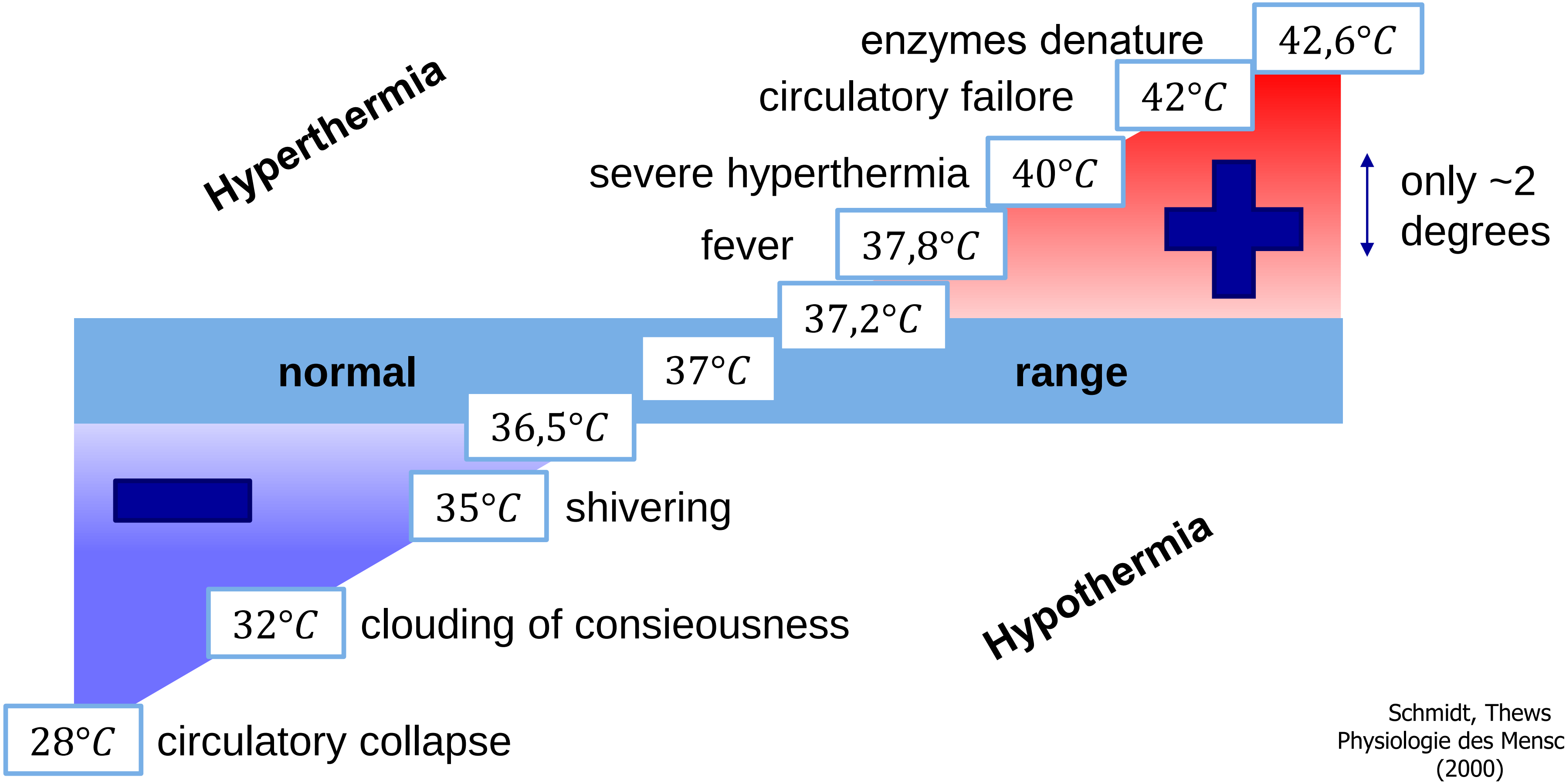
For mine rescue:
Similiar Temperatures, but even higher relative humidities!

Outline

1	Body Core temperature
2	Thermoregulation mechanisms in different environments
3	Core temperature measurement technologies
4	Dräger's experience with non-invasive core temperature measurements

Physiology

Interaction between physical and biochemical processes in cells, tissues and organs



Hyperthermia

enzymes denature 42,6°C

circulatory failore 42°C

severe hyperthermia 40°C

fever 37,8°C

37,2°C

only ~2 degrees

normal 37°C range

36,5°C

35°C shivering

32°C clouding of consieousness

28°C circulatory collapse

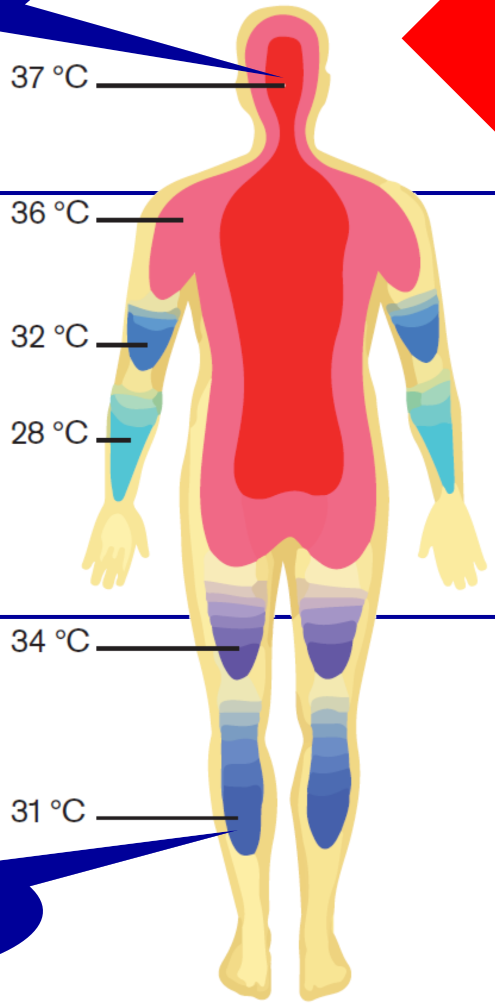
Hypothermia

Schmidt, Thews
Physiologie des Menschen
(2000)

Body core temperature

core temperature

is kept constant



muscle efficiency

$\eta \approx 25\%$

(depending on exercise and training level)

80 W metabolism

300 W heat generation

100 W mechanical effort

380 W heat removal

$$\frac{\dot{Q}}{C_{Body}} = \frac{\Delta T}{\Delta t}$$

$$\frac{380W}{335kWs/K} = \frac{0,7°C}{10min}$$

~for an 80kg person

periphery and surface

can vary strongly

Outline

1 Body Core temperature

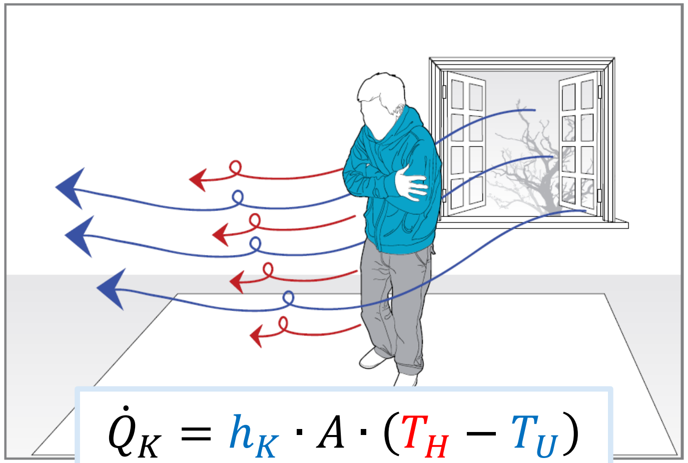
2 Thermoregulation mechanisms in different environments

3 Core temperature measurement technologies

4 Dräger's experience with non-invasive core temperature measurements

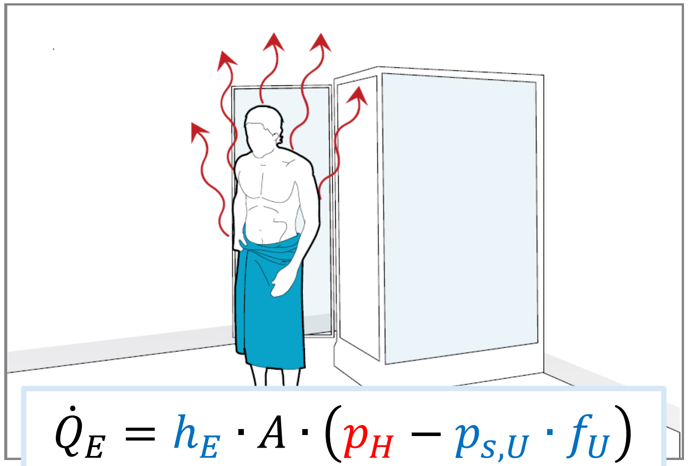
Mechanisms of heat removal

convection



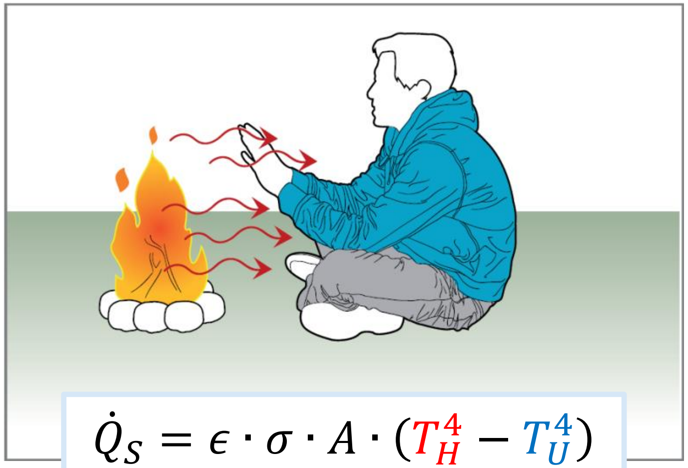
$$\dot{Q}_K = h_K \cdot A \cdot (T_H - T_U)$$

evaporation



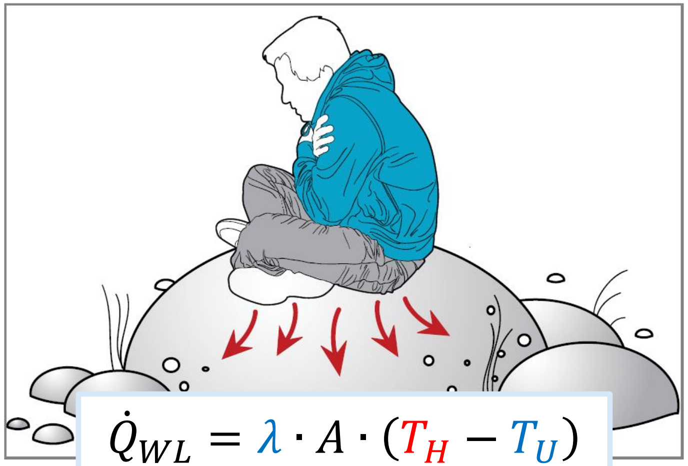
$$\dot{Q}_E = h_E \cdot A \cdot \left(p_H - p_{s,U} \cdot f_U\right)$$

radiation



$$\dot{Q}_S = \epsilon \cdot \sigma \cdot A \cdot (T_H^4 - T_U^4)$$

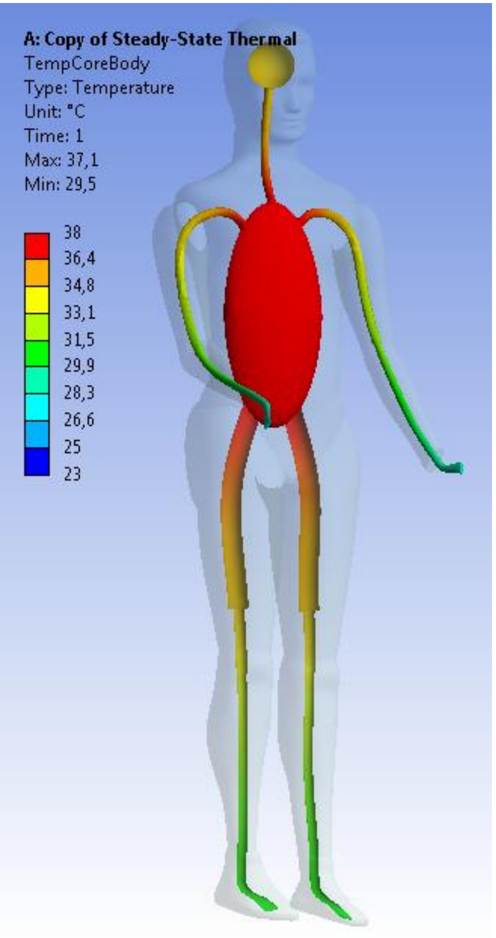
conduction



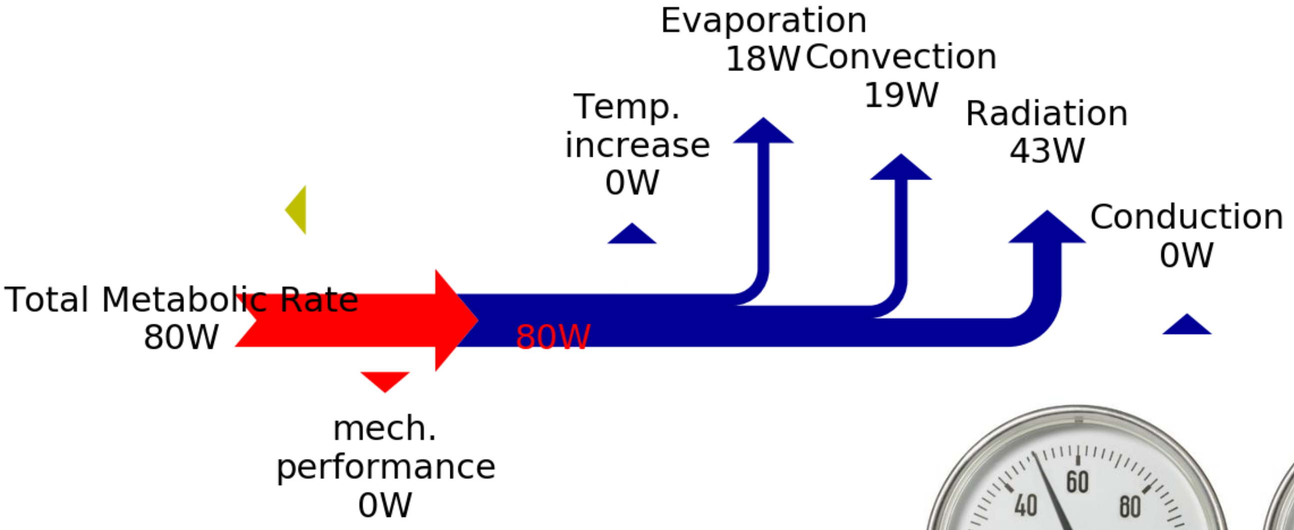
$$\dot{Q}_{WL} = \lambda \cdot A \cdot (T_H - T_U)$$

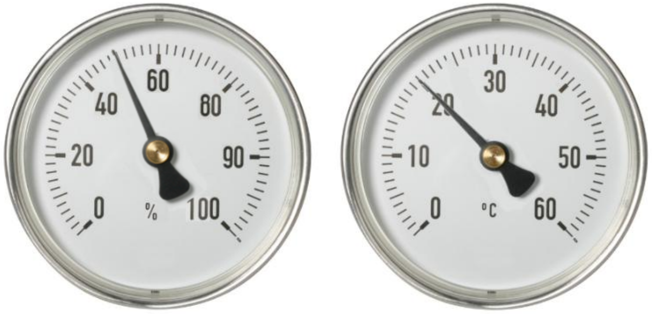
For all mechanisms, the surface temperature is significant

Heat transfer in different environments



heat transfer due to respiration is neglected





Humidity

Temperature

at rest

Total heat prod: 80W

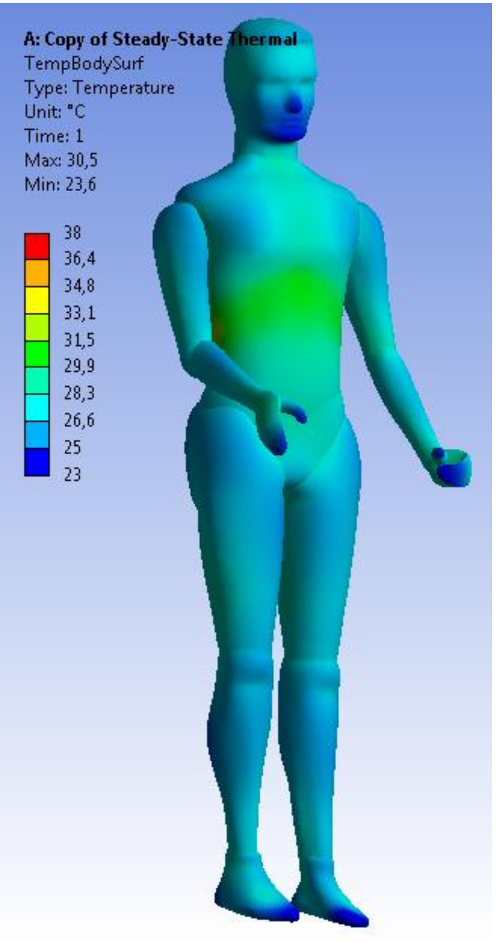
Env. Temperature: 20°C

Humidity: 50%

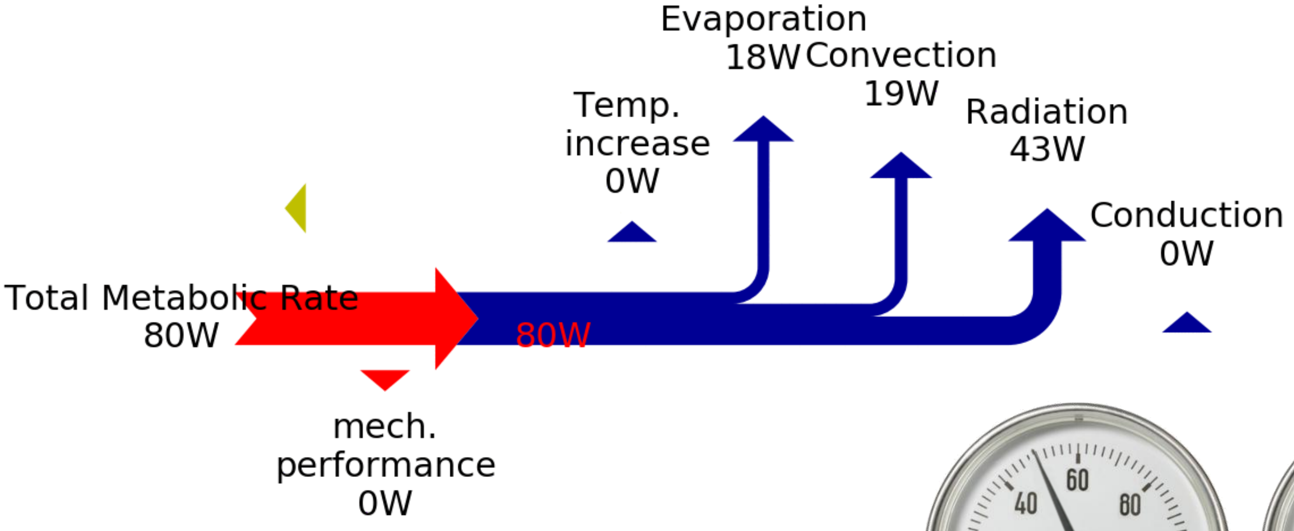
100W mech. Effort

Total heat prod: 380W

Heat transfer in different environments



heat transfer due to respiration is neglected



Evaporation
18W

Convection
19W

Radiation
43W

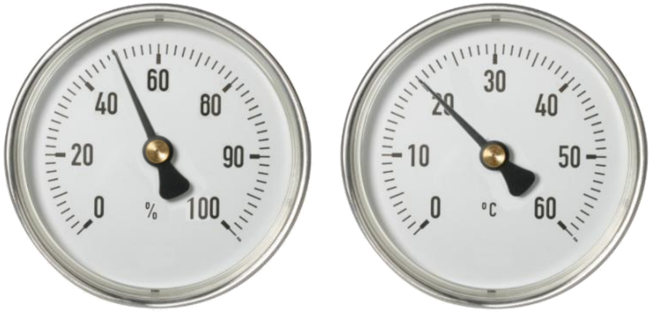
Temp. increase
0W

Conduction
0W

Total Metabolic Rate
80W

80W

mech. performance
0W



Humidity

Temperature

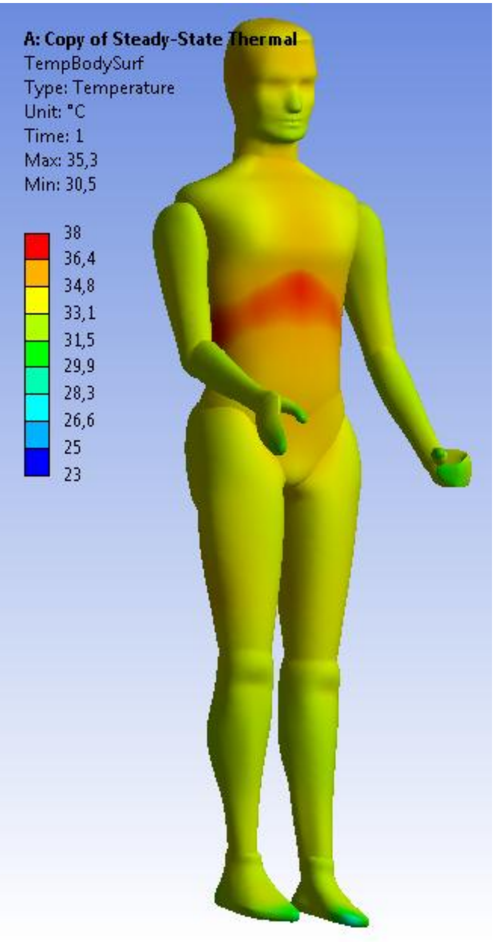
100W mech. Effort

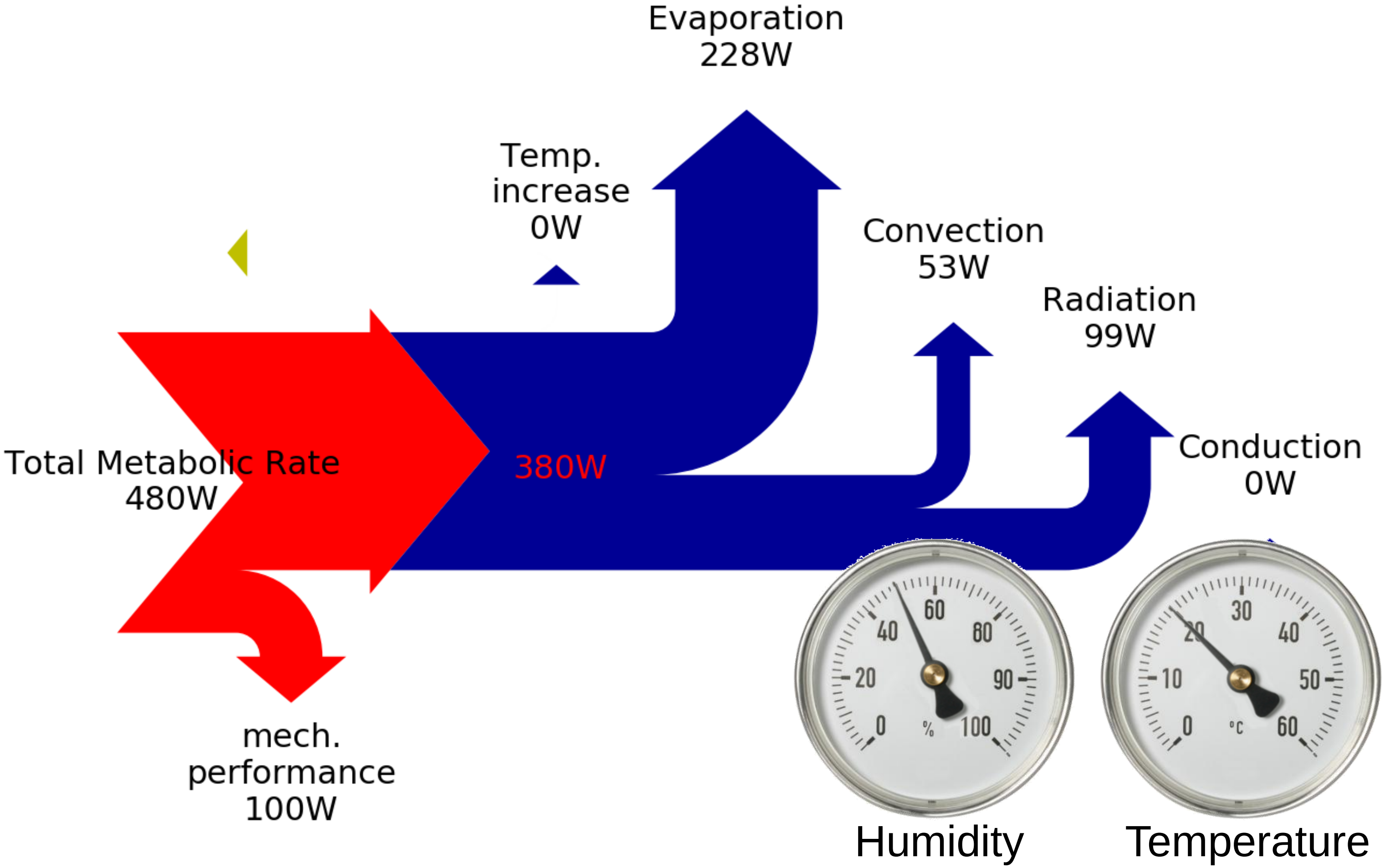
Total heat prod: 380W

Env. Temperature: 20°C

Humidity: 50%

Heat transfer in different environments





100W mech. Effort

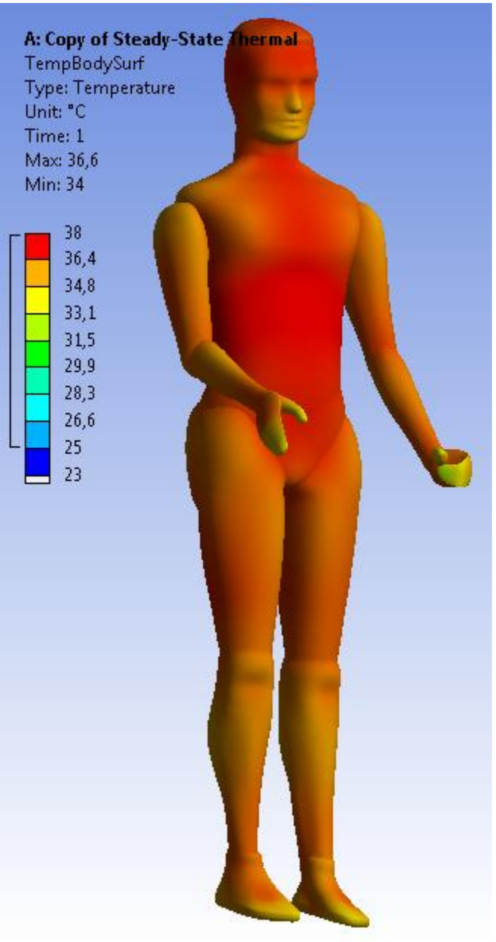
Total heat prod: 380W

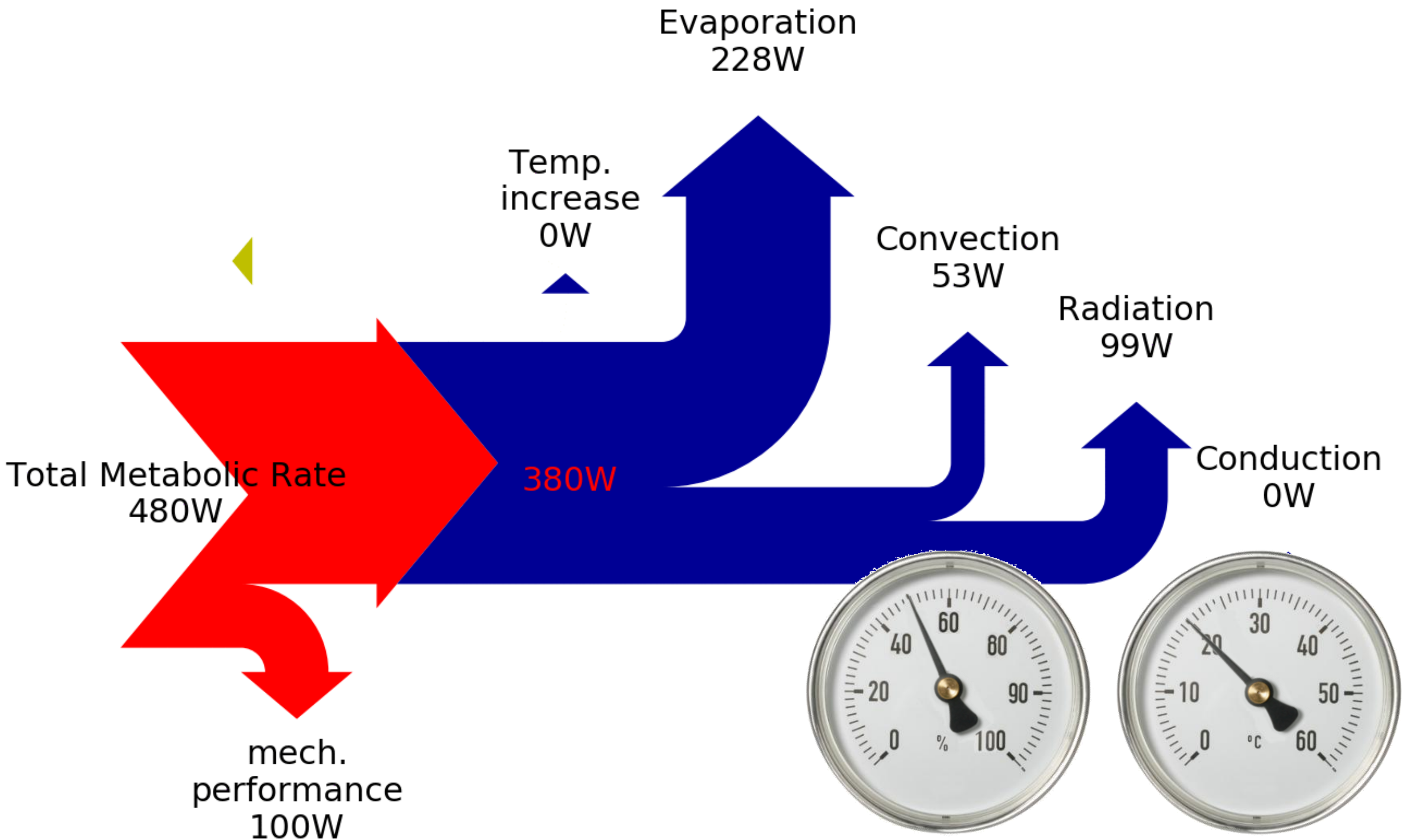
Env. Temperature: 20°C

Humidity: 50%

Env. Temperature: 35°C

Heat transfer in different environments





Evaporation
228W

Temp.
increase
0W

Convection
53W

Radiation
99W

Conduction
0W

Total Metabolic Rate
480W

380W

mech.
performance
100W

Humidity

Temperature

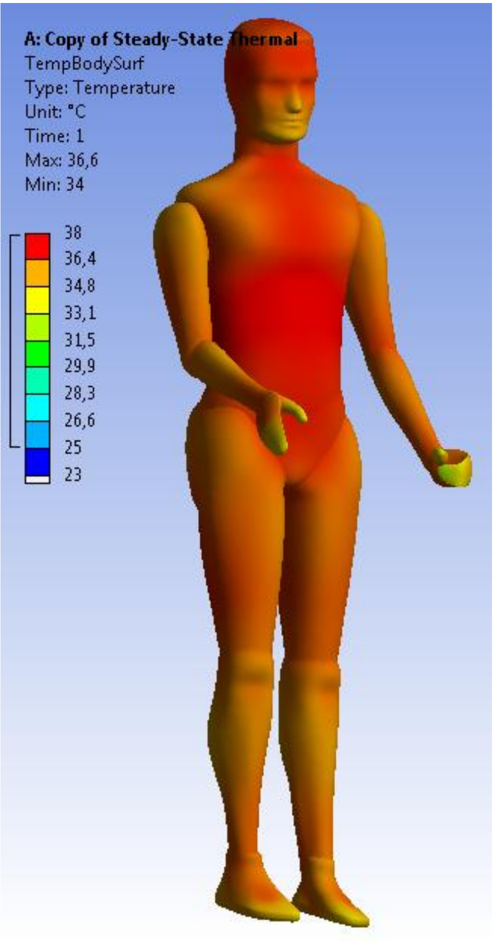
100W mech. Effort

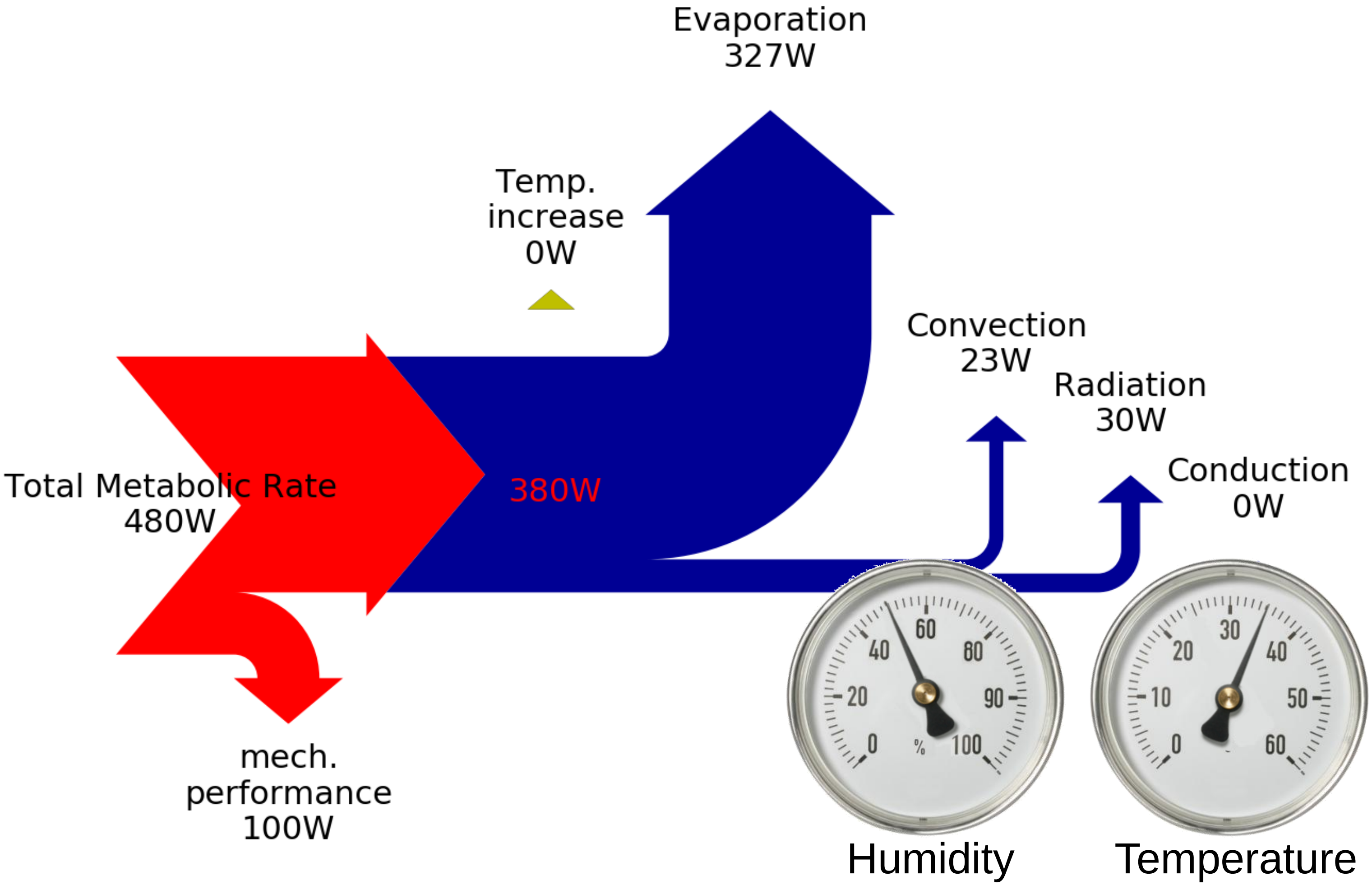
Total heat prod: 380W

Env. Temperature: 35°C

Humidity: 50%

Heat transfer in different environments





Evaporation
327W

Temp.
increase
0W

Convection
23W

Radiation
30W

Conduction
0W

Total Metabolic Rate
480W

380W

mech.
performance
100W

Humidity

Temperature

100W mech. Effort

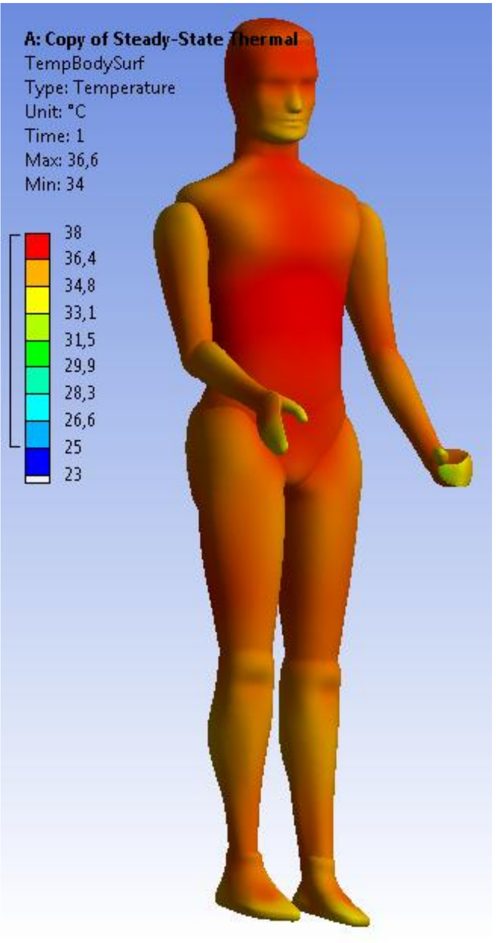
Total heat prod: 380W

Env. Temperature: 35°C

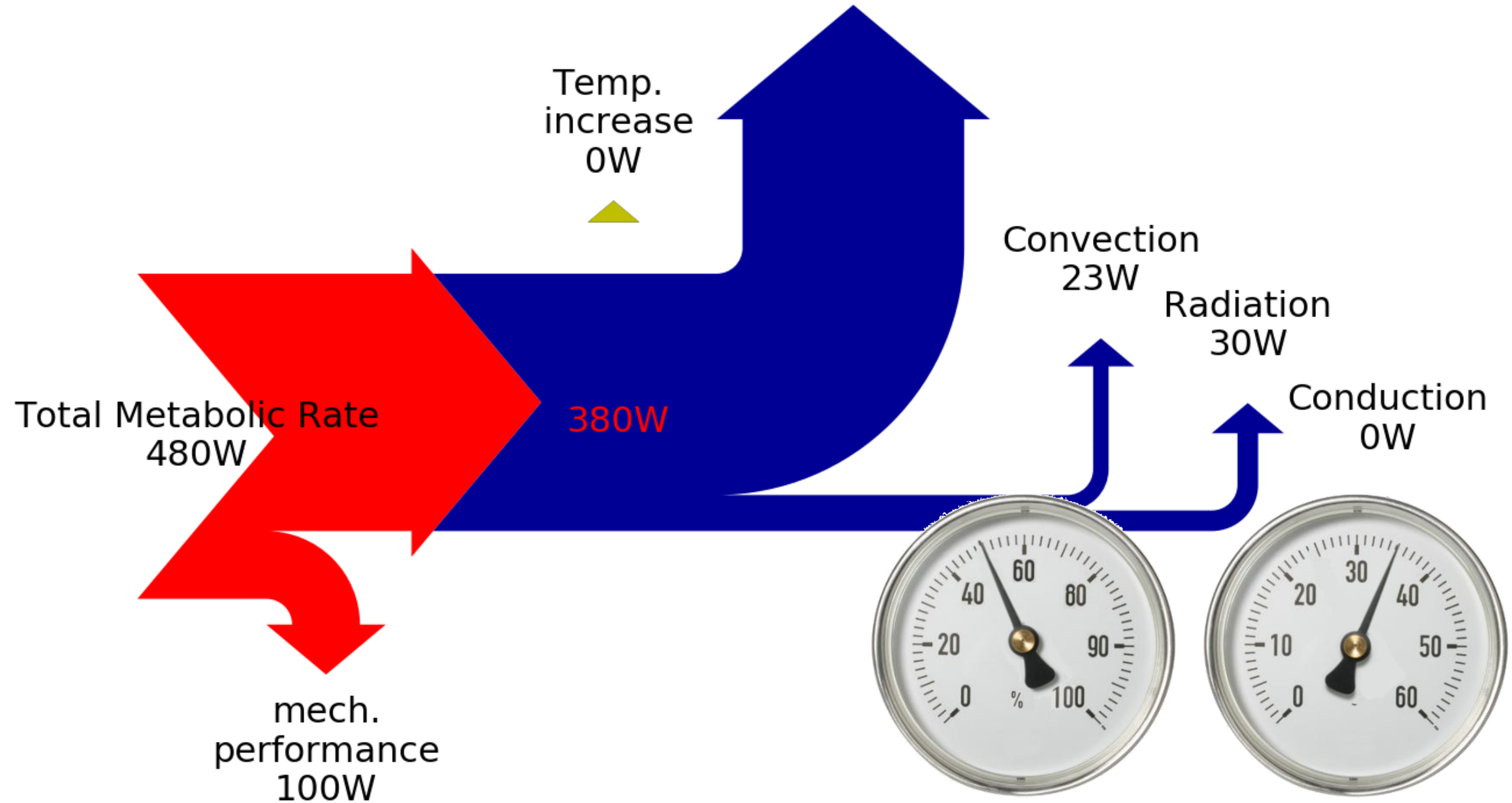
Humidity: 50%

Humidity: 90%

Heat transfer in different environments



$+0,45\ {}^{\circ C}/_{10min}$



Evaporation
327W

Temp.
increase
0W

Convection
23W

Radiation
30W

Conduction
0W

Total Metabolic Rate
480W

380W

mech.
performance
100W

Humidity

Temperature

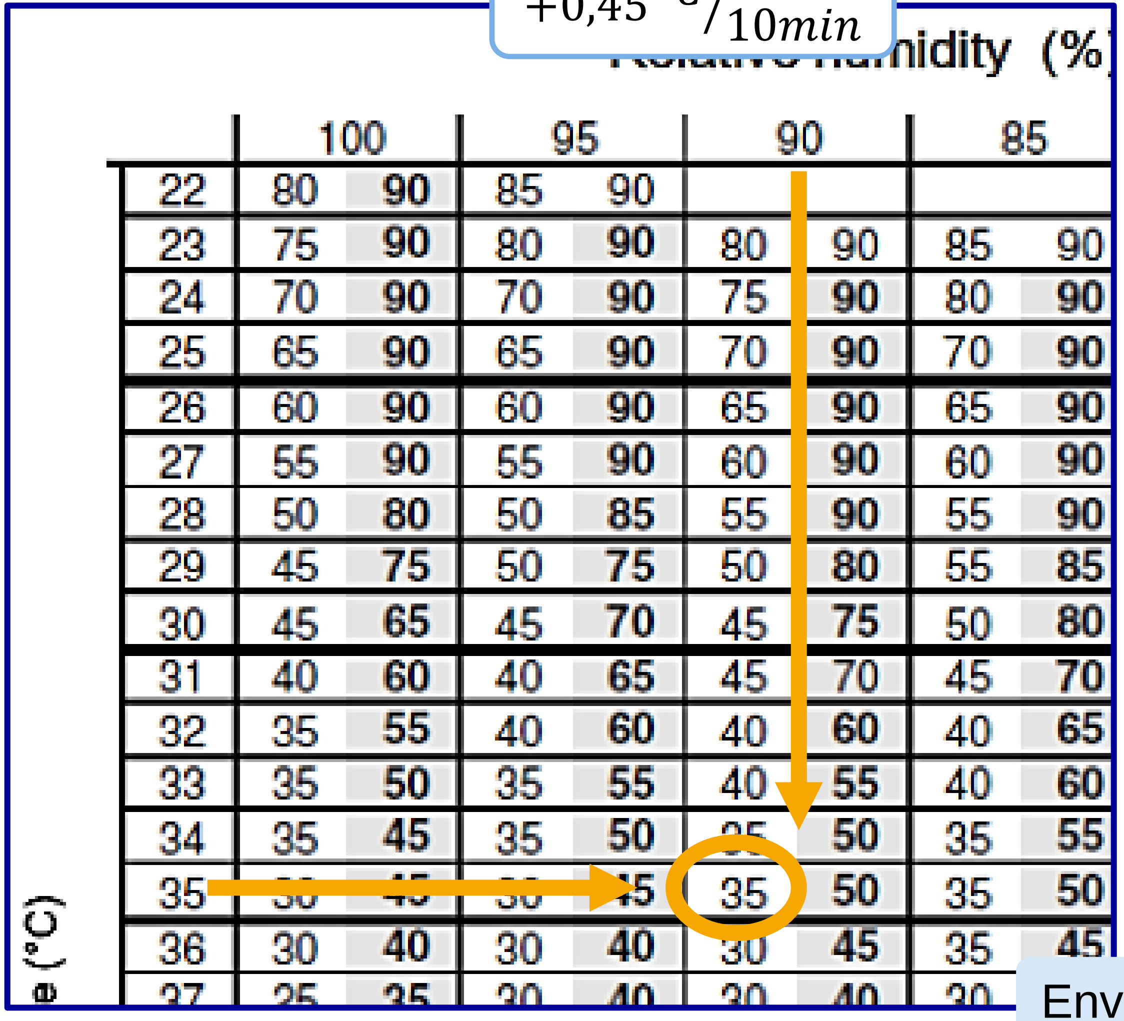
100W mech. Effort

Total heat prod: 380W

Env. Temperature: 35°C

Humidity: 90%

Comparison to Climate Tables



$+0,45\ {}^{\circ}C/_{10min}$

Relative humidity (%)

	100		95		90		85	
22	80	90	85	90				
23	75	90	80	90	80	90	85	90
24	70	90	70	90	75	90	80	90
25	65	90	65	90	70	90	70	90
26	60	90	60	90	65	90	65	90
27	55	90	55	90	60	90	60	90
28	50	80	50	85	55	90	55	90
29	45	75	50	75	50	80	55	85
30	45	65	45	70	45	75	50	80
31	40	60	40	65	45	70	45	70
32	35	55	40	60	40	60	40	65
33	35	50	35	55	40	55	40	60
34	35	45	35	50	35	50	35	55
35	30	45	30	45	35	50	35	50
36	30	40	30	40	30	45	35	45
37	25	35	30	40	30	40	30	

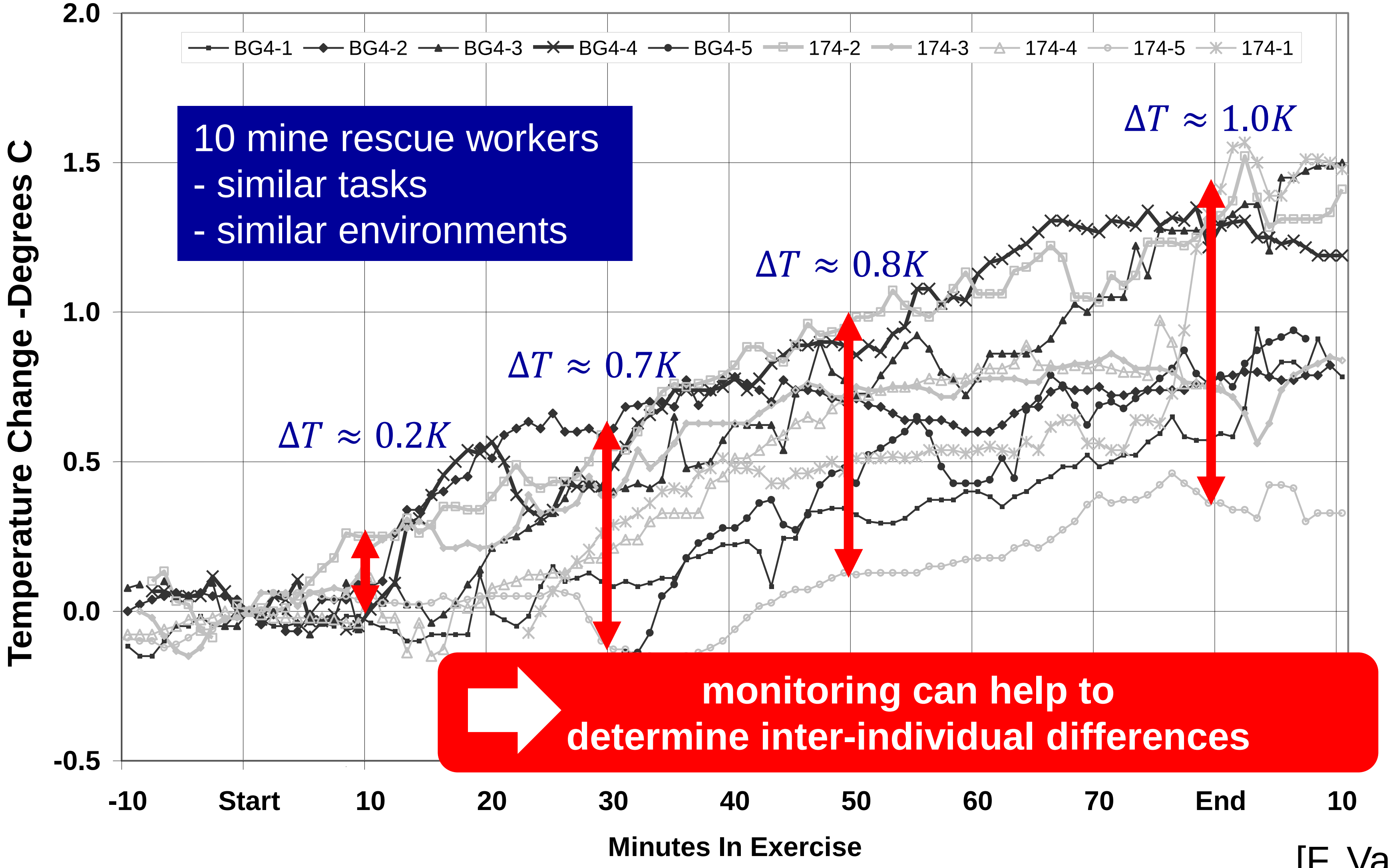
$+1,6\ {}^{\circ}C/_{35min}$

The WHO limit for core temperature is 39°C

Env. Temperature: 35°C

Humidity: 90%

Temperature trends show significant inter-individual differences in body efficiency and ability to remove heat



10 mine rescue workers
- similar tasks
- similar environments

monitoring can help to determine inter-individual differences

[F. Varley]

Outline

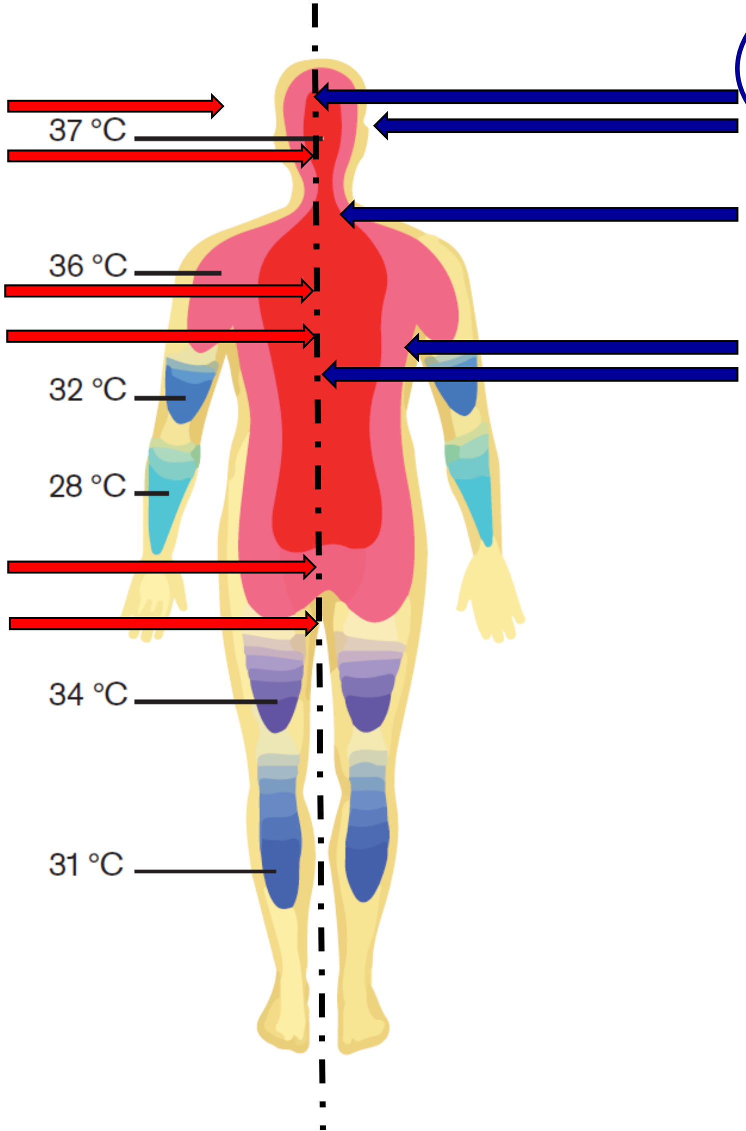
Conventional methods to measure core temperature

Invasive or mild invasive:

Head: ear (contact), oral
nasopharyngeal

Chest: esophageal
pulmonary artery
(Gold standard)

Lower body: rectal
bladder



Non invasive:

Head: Ear (IR), forehead,
temple

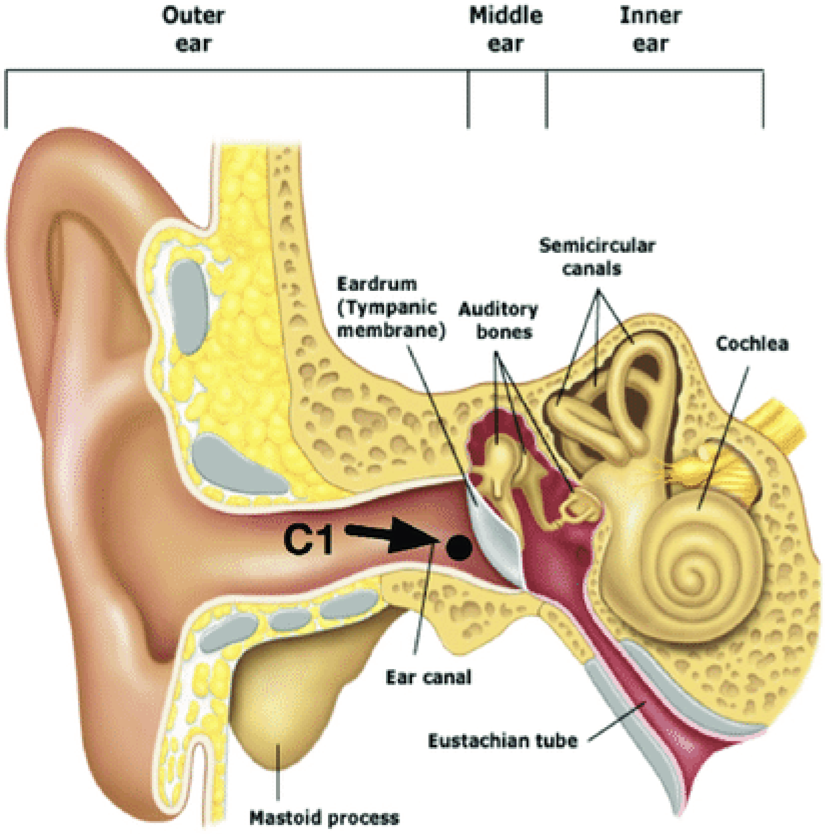
Neck: Carotis externa

Chest: ~~Axillar~~
Sternum

invasive

non-invasive

New Ideas to measure the core temperature



Yeoh et al. (2017)

- High accuracy only if measured at tympanic membrane
- high perfusion

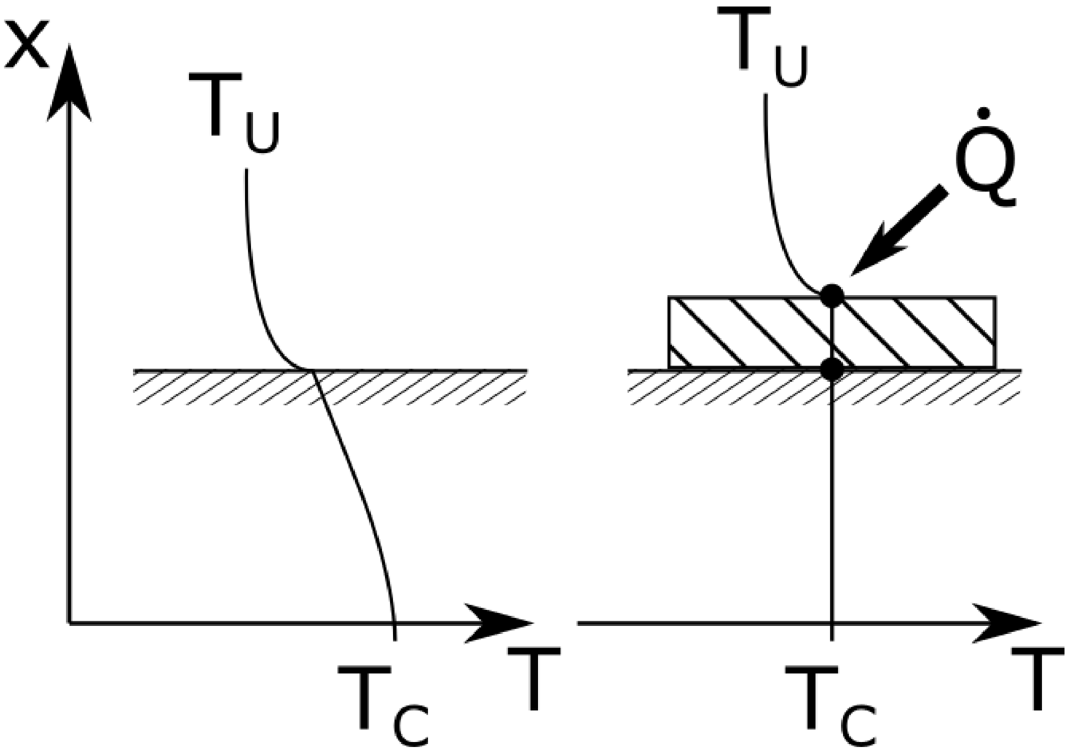
- but…
- ear chanal is not straight
- individually very different
- changes in environmental temperatures might affect local temperatures

Zero-Heat-Flux thermometry

- Two temperature measurements
- one heater

- heated until $T_1 = T_2$
- Then $T_1 = T_2 = T_C$

- only works for $T_C > T_U$
- poor performance when environmental conditions vary strongly
- higher energy consumption



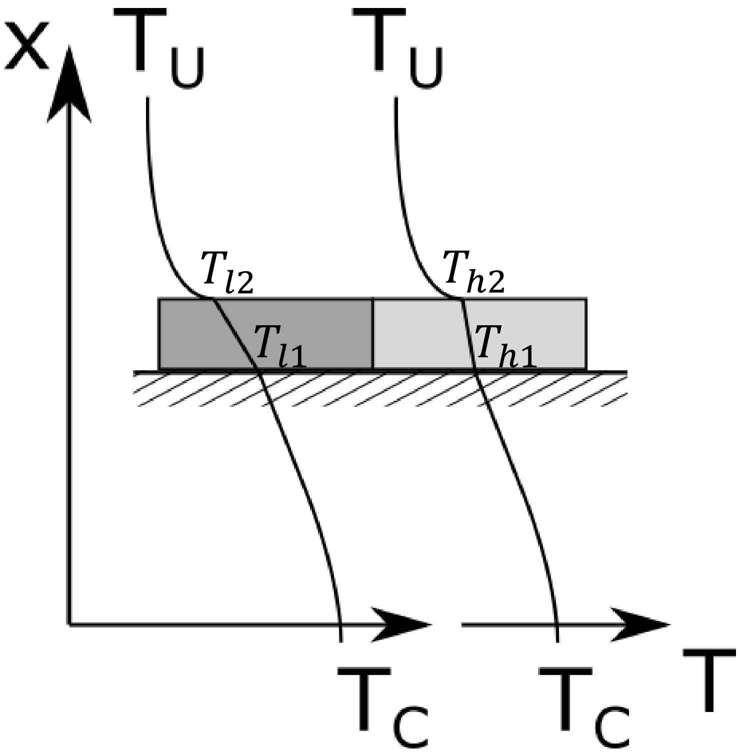
Bias: -0,23°C, SD=0,41°C

Eshragie et al. (2012)

Dual-Heat-Flux thermometry

- Four temperature sensors needed
- still under investigation
- sensor might need to cover a large area

$$\boldsymbol{k_T}(T_{h1} - \boldsymbol{T_C}) = k_h(T_{h2} - T_{h1})$$
$$k_T(T_{l1} - T_C) = k_l(T_{l2} - T_{l1})$$



Bias: 0,09°C, SD=0,13°C

Huang et al. (2013)

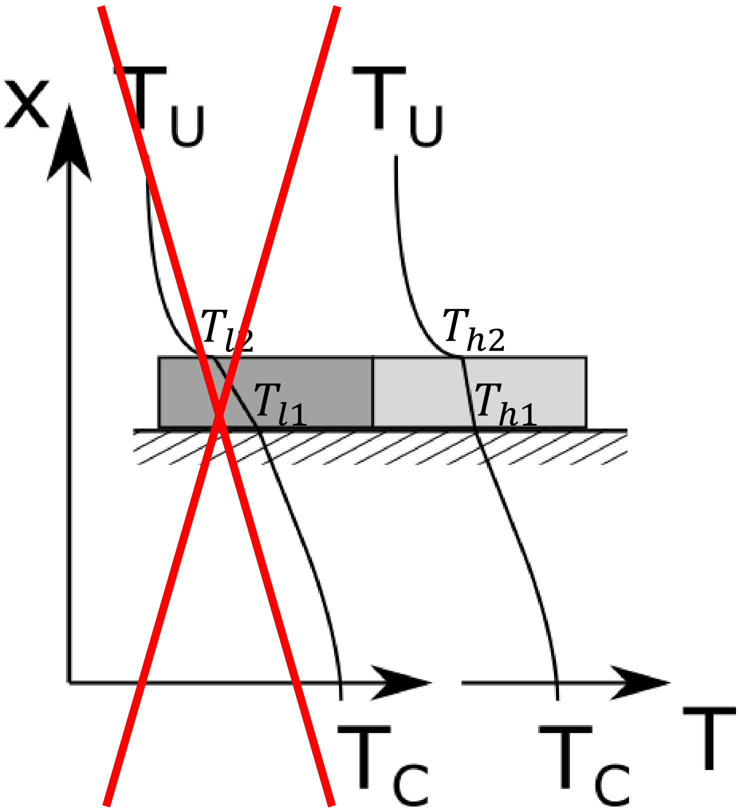
Dual-Heat-Flux thermometry

- Four temperature sensors needed
- still under investigation
- sensor might need to cover a large area

$$\boldsymbol{k_T}(T_{h1} - \boldsymbol{T_C}) = k_h(T_{h2} - T_{h1})$$

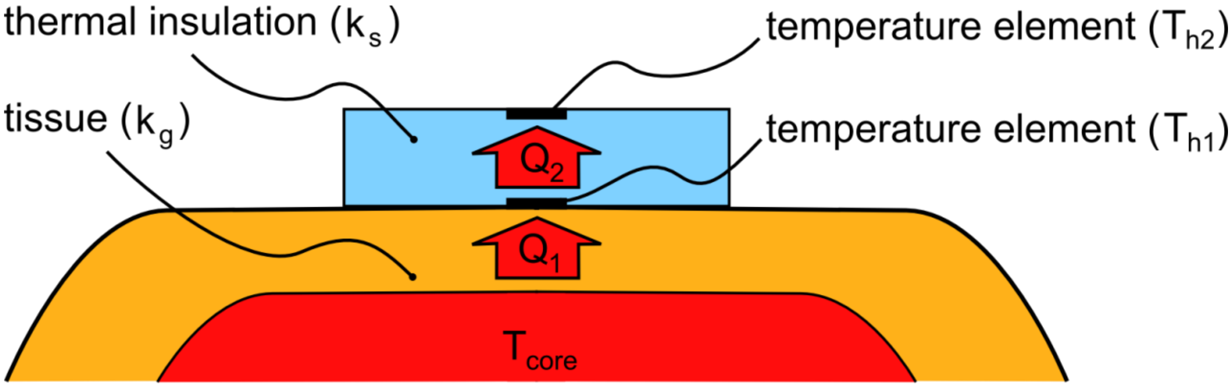
~~$k_T(T_{l1} - T_C) = k_l(T_{l2} - T_{l1})$~~

We found out:
$\boldsymbol{k_T}$ is similar for every human



Outline

Monitoring of body core temperature with Dräger Tcore



$$T_{core} = T_{h1} + \frac{k_s}{k_g}(T_{h1} - T_{h2})$$

- current design for clinical application
- identification of body core temperature with measurements on the human skin
- easy handling of the sensor
- non-invasive method

Study on patients undergoing surgery

MEDICAL
UNIVERSITY
OF VIENNA

OR

Method: 68 patients in OR and ICU
Validation of the reusable Double Sensor
with oesophageal temperature
on two forehead positions

Bias: -0,xx°C, SD=0,29°C

(2002)

b) study on fire fighters under physiological strain:

Dräger

Method: 20 subjects under physiological strain under three different controlled ambient conditions on “spider”, vertex, sternum and forehead position

Bias: -0,xx°C, SD=0,33°C

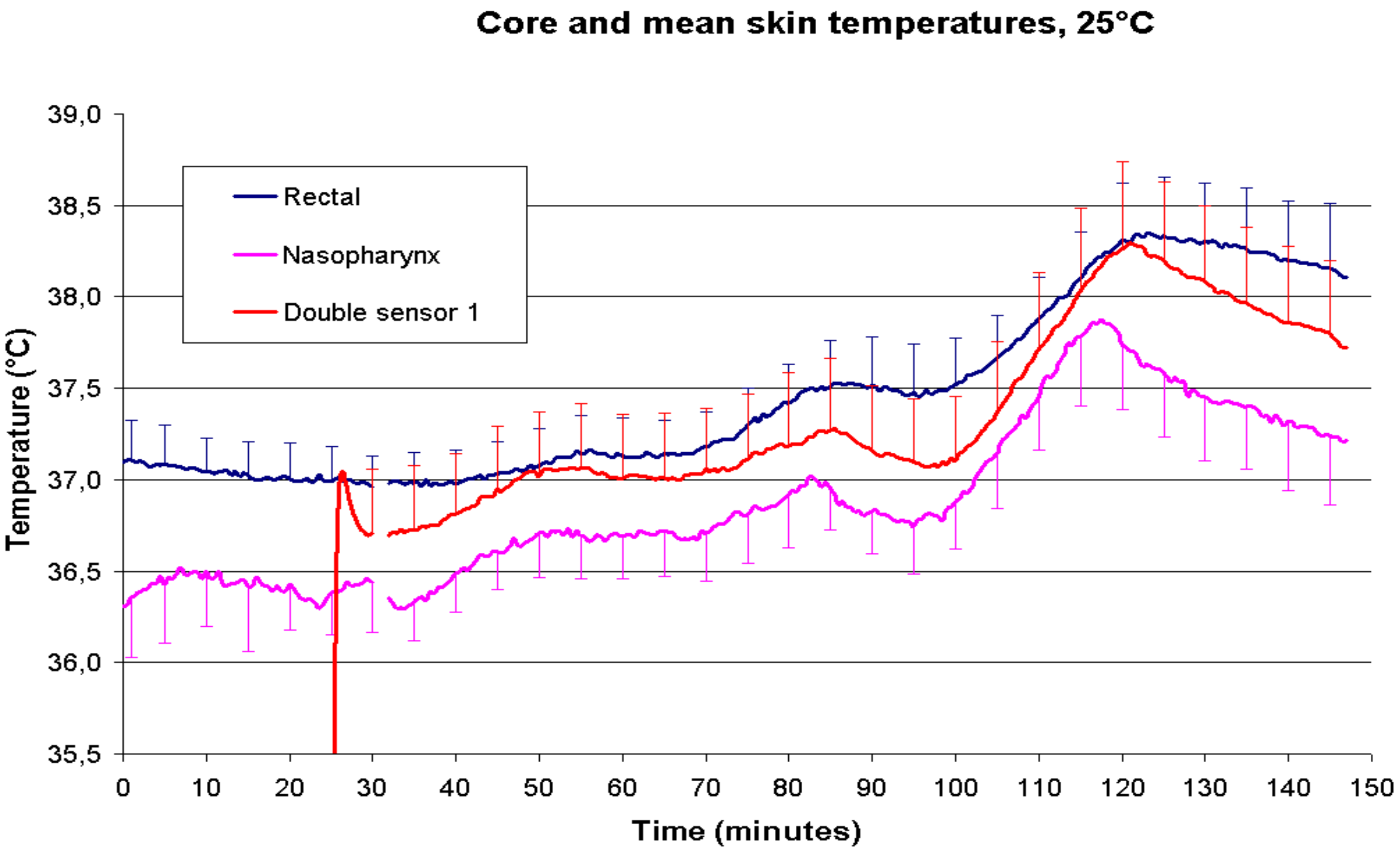
(2002)

Validation of the Double Sensor with rectal temperature

SINTEF

Fire fighter study

mean core temperatures at 25 °C ambient temperature



Comparison with invasive temperatures

Thermometers	Standard deviation	Source
Oesophagus (pulmonary artery)	0.30 °C	Lefrant et.al.: Temperature measurrementin intensive care patients: comparison of urinary bladder, oesophageal, rectal, axillary, and inguinal methods versus pulmonary artery core method; Intensive Care Med (2003) 29: 414-418
Oral (pulmonary artery)	0.43 °C	Lawson et.al.: Accuracy and precision of noninvasive temperature measurement in adutl intensive care patients, American Journal of Critical Care, Sept. 2007, Volume 16, No.5 p.485 – 496
Rectal (oesophagus)	0.41 °C	Bräuer et.al.: Bestimmung der Körperkerntemperatur, Anaesthesist: 1997:46:683-688
Bladder (oesophagus)	0.34 °C 0.41 °C	Bräuer et.al.: Bestimmung der Körperkerntemperatur Anaesthesist: 1997:46:683-688 Bräuer et.al: Einfluss der Blasentemperatur bei intraabdominalen Eingriffen: Anästhesiol Intensivmed Notfallmed Schmerzther 2000;35
neonates (rectal)	0,15 °C	Kimberger et.al.: Accuracy and precision of a novel non-invasive core thermometer, BJA: May 2009
Double Sensor forehead (oesophagus)	0.29 °C	Gunga et.al.: A non-invasive device to continously determine heat strain in humans. J of Thermal Biology Vol. 33, Issue 5, p.297-307
vertex (rectal)	0.33 °C	

We can't be better than invasive methods! However, these are respectable results!

Monitoring of body core temperature with Dräger Tcore

Dräger Tcore at the International Space Station (ISS)

Summary

Trend of Body core temperature depends on…

- environmental conditions
- work load
- training level
- clothing
- hydration

$$T_c = f(\ldots)$$

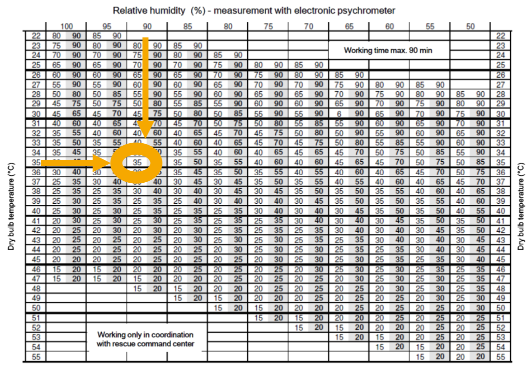
New technologies make non-invasive core temperature monitoring possible.

Monitoring of core temperature might…

- reduce the risk of heat strokes/heat stress
- allow a selective control of operation time
- reduce risk of overestimation of one‘s capabilities

Can new technologies support established routines?

Tables



Relative humidity (%) - measurement with electronic psychrometer

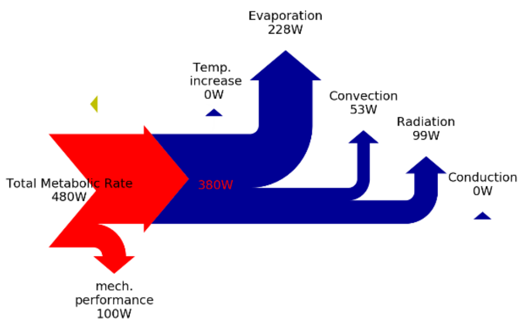
Dry bulb temperature (°C)	100		95		90		85		80		75		70		65		60		55		50		Dry bulb temperature (°C)
22	80	90	85	90																			22
23	75	90	80	90	80	90	85	90							Working time max. 90 min								23
24	70	90	70	90	75	90	80	90	85	90													24
25	65	90	65	90	70	90	70	90	75	90	80	90	85	90									25
26	60	90	60	90	65	90	65	90	70	90	75	90	80	90	85	90							26
27	55	90	55	90	60	90	60	90	65	90	70	90	70	90	75	90	80	90	85	90			27
28	50	80	50	85	55	90	55	90	60	90	65	90	65	90	70	90	75	90	80	90	85	90	28
29	45	75	50	75	50	80	55	85	55	90	60	90	60	90	65	90	70	90	75	90	80	90	29
30	45	65	45	70	45	75	50	80	50	85	55	90	55	90	6	90	65	90	70	90	75	90	30
31	40	60	40	65	[illegible]	70	45	70	50	75	50	80	55	85	55	90	60	90	65	90	70	90	31
32	35	55	40	60	40	60	40	65	45	70	45	75	50	80	50	90	55	90	60	90	65	90	32
33	35	50	35	55	40	55	40	60	40	65	45	70	45	75	50	80	55	85	55	90	60	90	33
34	35	45	35	[illegible]	[illegible]	[illegible]	35	55	40	60	40	65	45	65	45	70	50	75	50	85	55	90	34
35	[illegible]	[illegible]	[illegible]	[illegible]	35	[illegible]	35	50	35	55	40	60	40	60	45	65	45	70	50	75	50	85	35
36	30	40	30	[illegible]	[illegible]	[illegible]	35	45	35	50	35	55	40	55	40	60	40	65	45	70	50	75	36
37	25	35	30	40	[illegible]	40	30	45	30	45	35	50	35	55	40	55	40	60	40	65	45	70	37
38	25	35	25	35	30	40	30	40	30	45	30	45	35	50	35	50	35	55	40	60	40	65	38
39	25	30	25	35	25	35	25	40	30	40	30	40	30	45	35	50	35	50	35	55	40	60	39
40	25	30	25	30	25	35	25	35	25	35	30	40	30	40	30	45	35	50	35	50	40	55	40
41	20	30	25	30	25	30	25	35	25	35	25	35	30	40	30	40	30	45	35	50	35	50	41
42	20	25	20	30	20	30	20	30	25	35	25	35	25	35	30	40	30	40	30	45	35	50	42
43	20	25	20	25	20	25	20	30	25	30	25	30	25	35	25	35	30	40	30	40	30	45	43
44	20	25	20	25	20	25	20	25	20	30	25	30	25	30	25	35	25	35	30	40	30	45	44
45	20	20	20	25	20	25	20	25	20	25	20	30	25	30	25	30	25	35	25	35	30	40	45
46	15	20	15	20	20	20	20	25	20	25	20	25	20	30	25	30	25	30	25	35	25	35	46
47	15	20	15	20	15	20	20	20	20	25	20	25	20	25	20	30	25	30	25	30	25	35	47
48					15	20	15	20	20	20	20	25	20	25	20	25	20	30	25	30	25	35	48
49							15	20	15	20	20	20	20	25	20	25	20	25	20	30	25	30	49
50									15	20	15	20	20	20	20	25	20	25	20	25	20	30	50
51											15	20	15	20	20	20	20	25	20	25	20	25	51
52													15	20	15	20	20	20	20	25	20	25	52
53			Working only in coordination with rescue command center												15	20	15	20	20	25	20	25	53
54																	15	20	15	20	20	25	54
55																			15	20	20	20	55

planning based on:

worst case environment

average human physiology

Simulations



planning based on:

variable environment

average human physiology

Monitoring

accounts for:

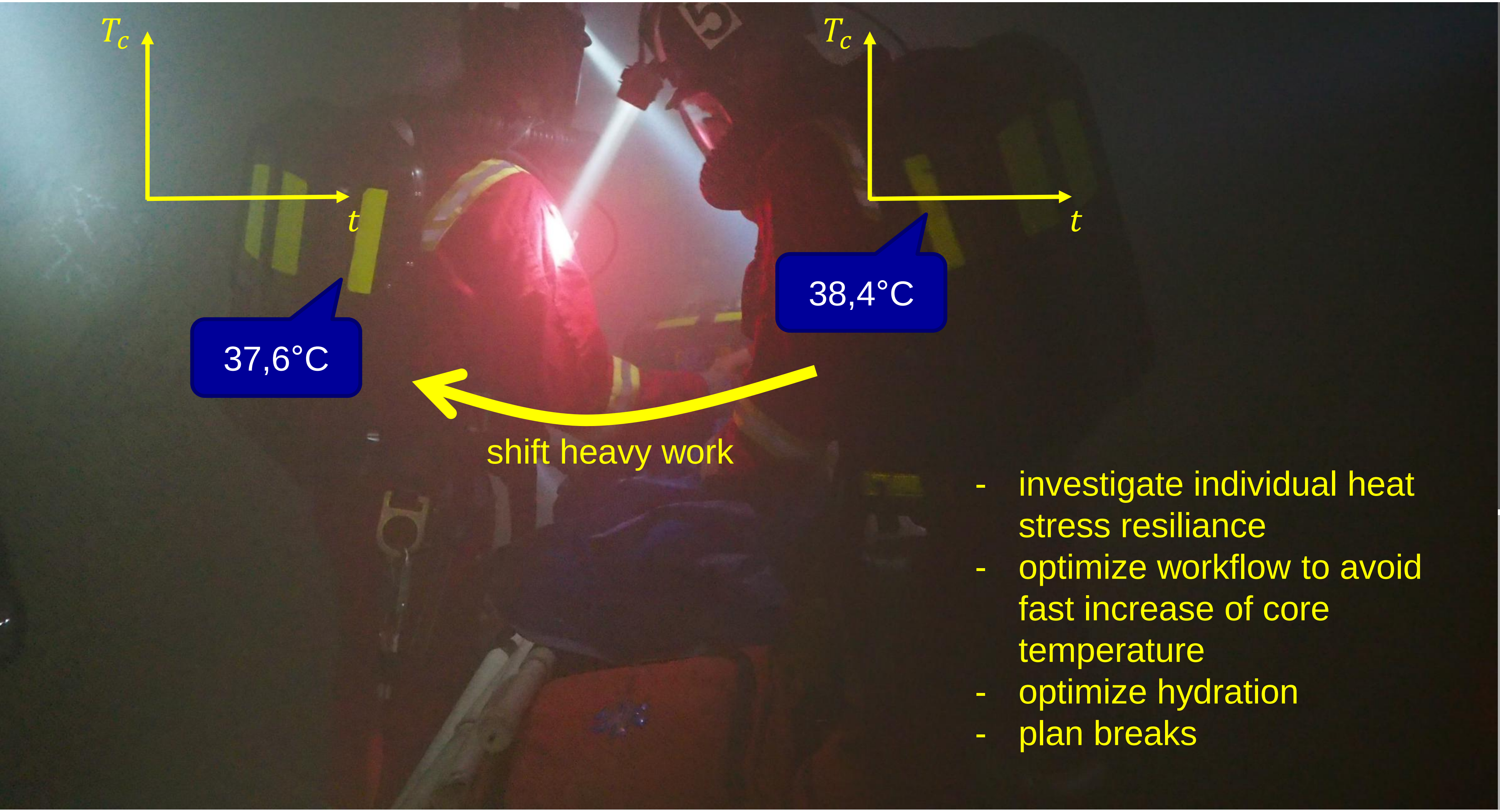
variable environment

individual human physiology

What‘s your opinion?
We appreciate your comments and are looking forward to discussing this topic with you.

Backup

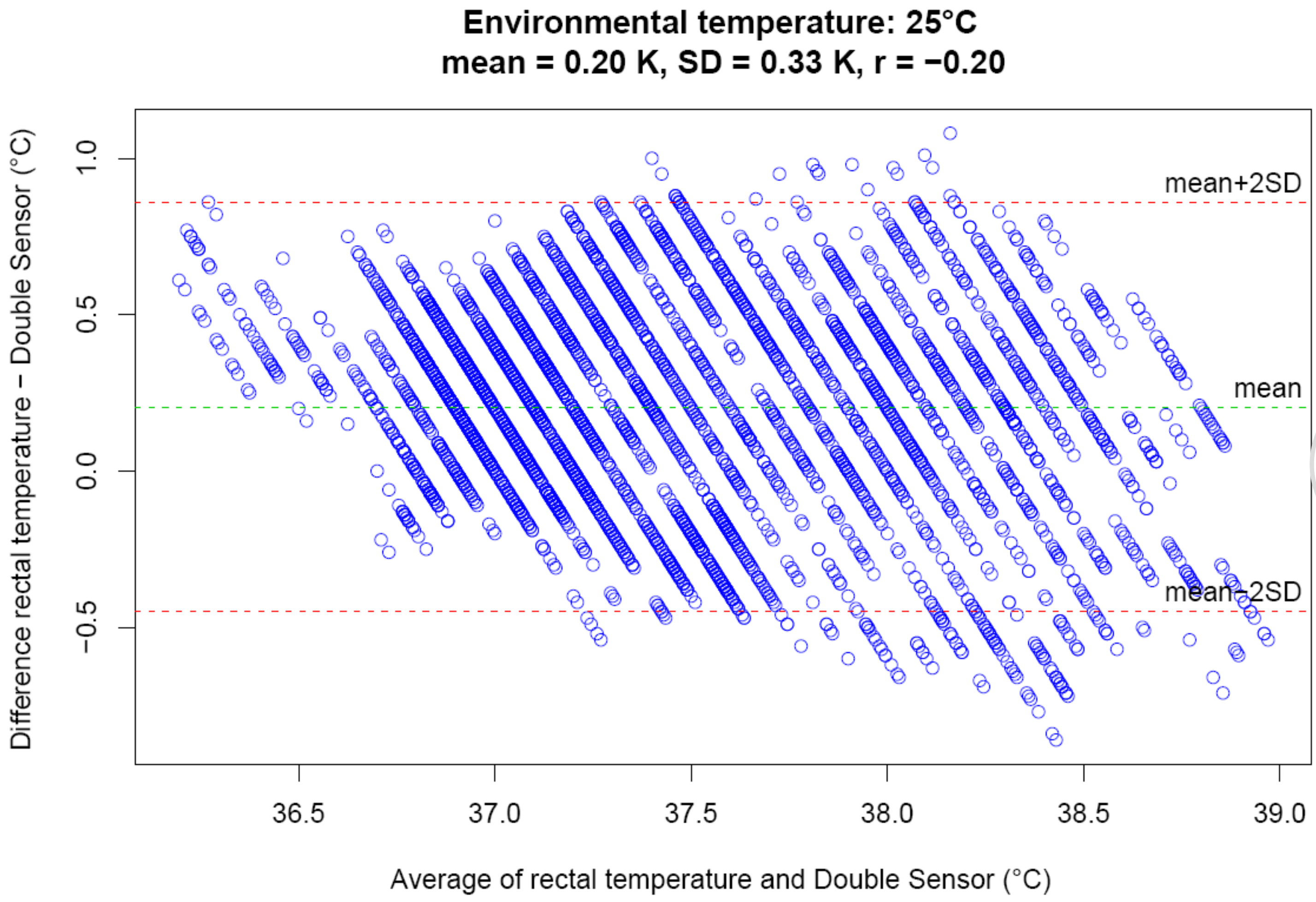
What can we do with it?
In training and during a mission



- investigate individual heat stress resiliance
- optimize workflow to avoid fast increase of core temperature
- optimize hydration
- plan breaks

Bland Altman diagram
at 25 °C ambient temperature

published:
ICEE 2005 Ystad



At 25 °C

mean = 0.20 K

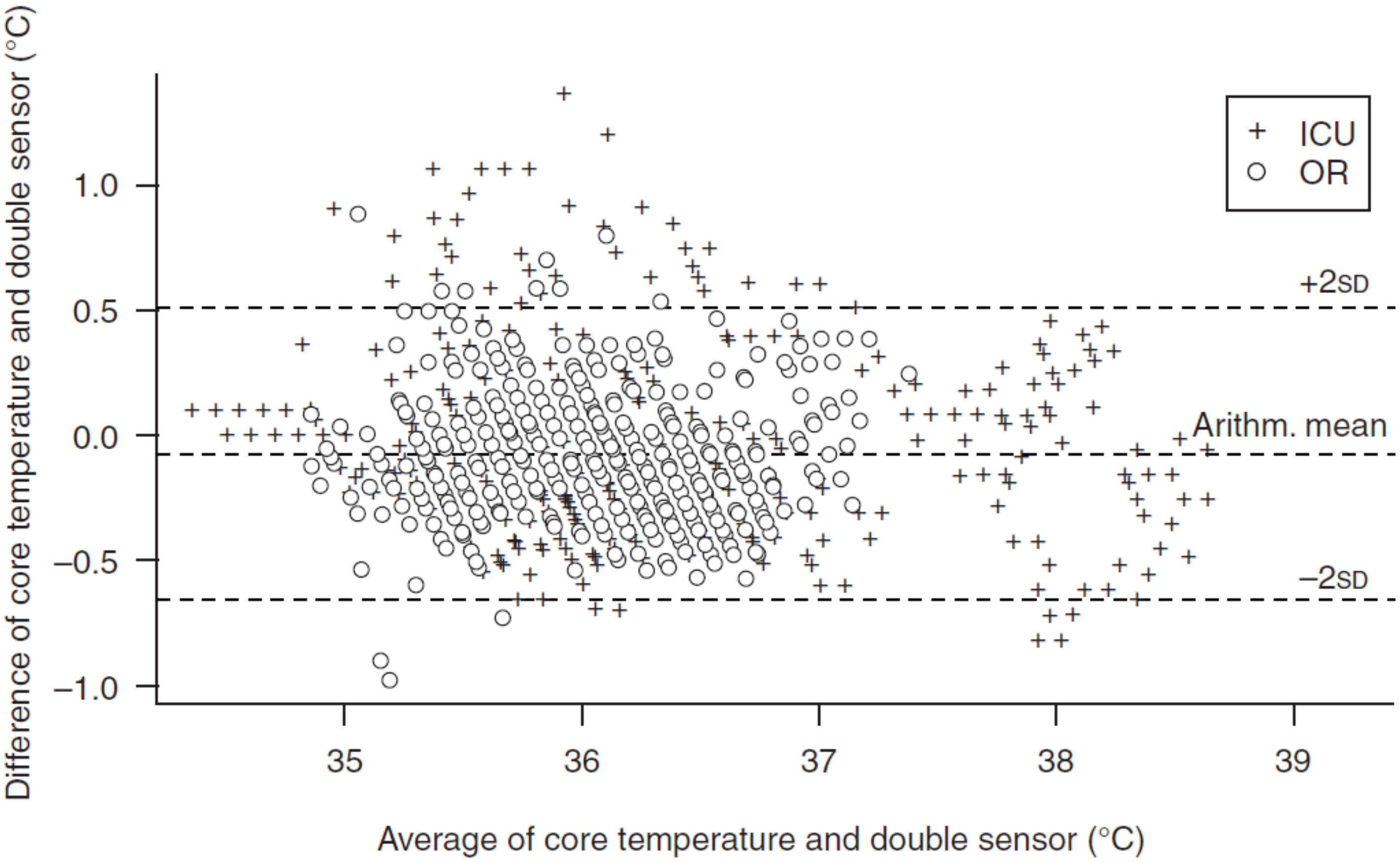
SD = 0.33 K

CCC = 0.81

Gunga et.al.: A non-invasive device to continuously determine heat strain in humans; Journal of thermal biology; March 2008

Bland Altman diagram

at 25 °C ambient temperature



mean = -0.08 K

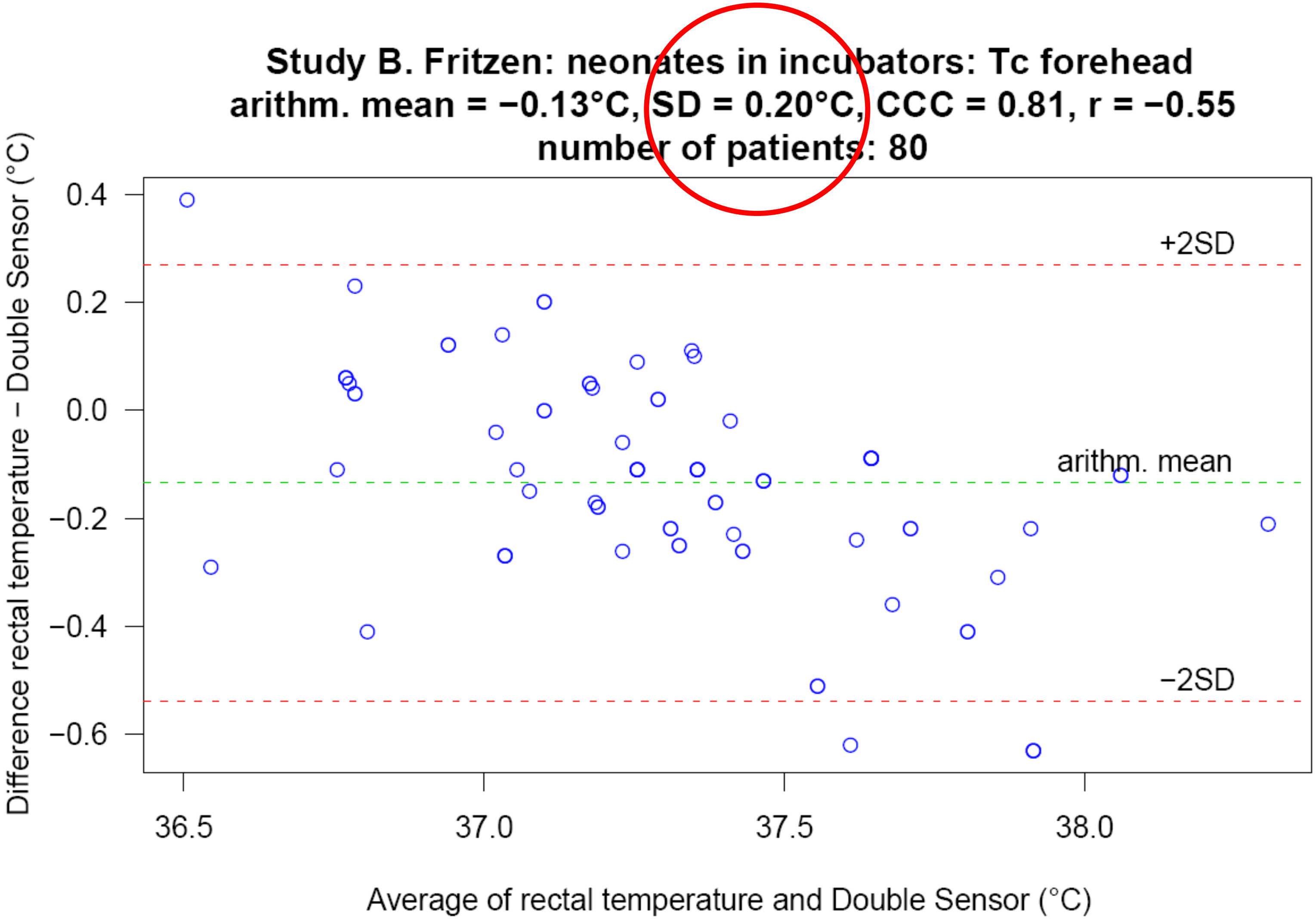
SD = 0.29 K

CCC = 0.93

Kimberger et al. (2009)

a) Study on neonates

80 patients in incubators: forehead position



First concept proof on neonates in incubators

Validation of the Double Sensor on 80 neonates in incubators with rectal temperature on forehead and abdominal position

Bias: -0,18°C, SD=0,15°C

(2002)

Published 2002:
Standard deviation: 0.15 °C