Age dependence of thermoregulation, heating of the eye, relationship between SAR and temperature, thermal model for pregnant woman (ambient heat versus HF)

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ICNIRP
INTERNATIONAL COMMISSION ON NON-IONIZING RADIATION PROTECTION

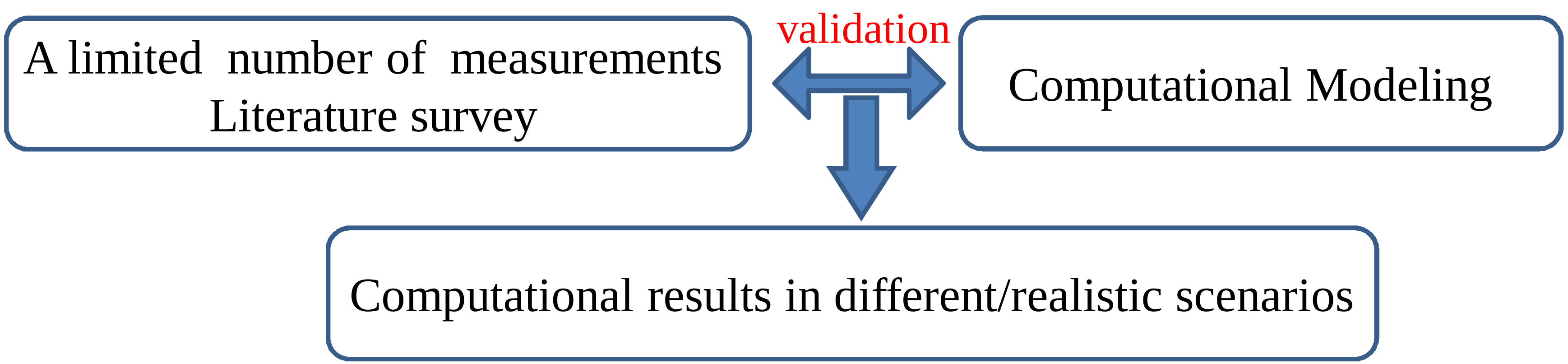
ICNIRP/WHO Workshop on Thresholds of Thermal Damage

World Health Organization

Computational Method and Modeling of Thermophysiology

Motivation & Computational Methods

- It is unrealistic to conduct many measurements for excessive heat load due to ethical reasons.
- We can simulate temperature elevation for ambient heat and microwaves after computational methods are validated.
- Multi-physics modeling: Electromagnetics and thermodynamics (considering core temperature change) in anatomically based model (50+ tissues)
- Plus the thermoregulatory response (vasodilation, sweating)



Bioheat Transfer Equation

Heat conduction

$$C(\mathbf{r})\rho(\mathbf{r})\frac{dT(\mathbf{r},t)}{dt} = \nabla\cdot(K(\mathbf{r})\nabla T(\mathbf{r},t)) +$$

Blood temperature

$$\rho(SAR(\mathbf{r})) - b(\mathbf{r},t)(T(\mathbf{r}) - T_b(t)) + A(\mathbf{r})$$

EM power Blood perfusion Metabolic Rate

C: Specific heat[J/(^{o}C kg)]

H. H. Pennes, J. Appl. Physiol. 1948

K:Heat conductivity[W/(^{o}C m)]

b:term associated with blood perfusion [W/(m^{3} ^{o}C)]

$$-K(\vec{r})\frac{\partial T(\vec{r},t)}{\partial n}S = H\cdot(T_s(\vec{r},t)-T_a) + SW(\vec{r},T(\vec{r},t))$$

H: heat transfer coefficient[W/m^{2o}C], T_{air}:air temperature[^{o}C]

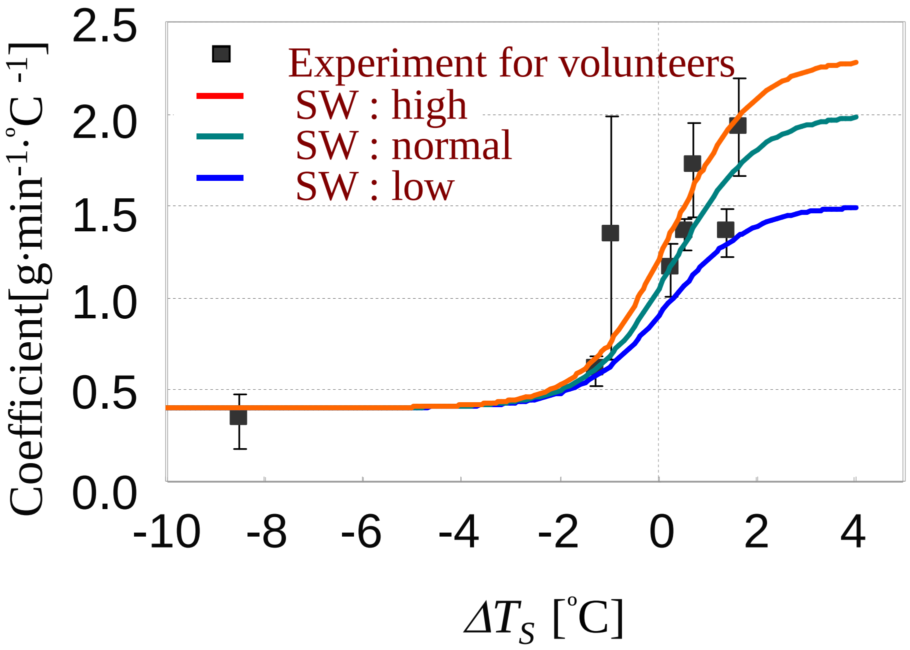
SW: heat loss due to sweating

Modeling of Perspiration

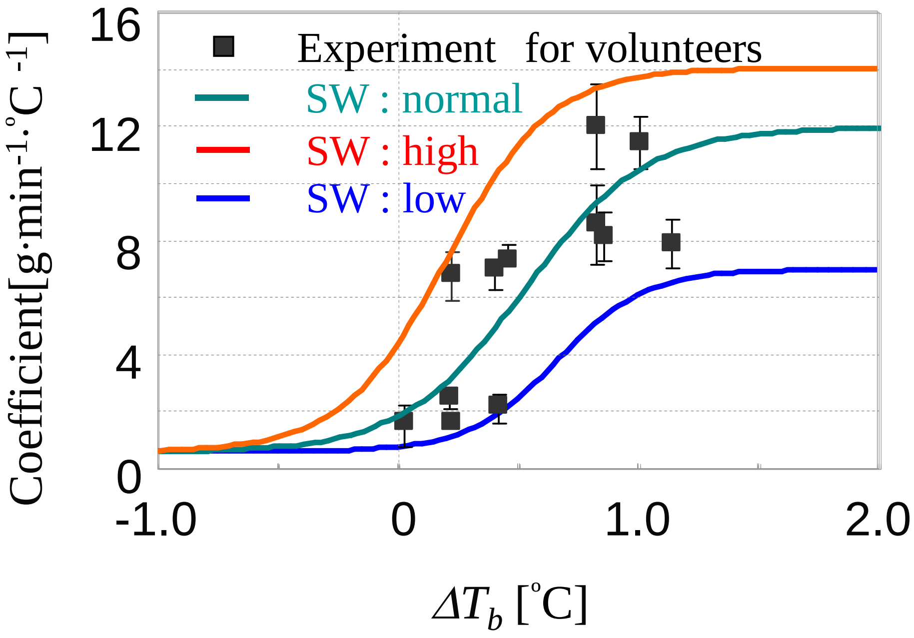
$$SW(\vec{\boldsymbol{r}},t) = \left(\alpha \Delta T_{Savg} + \beta \Delta T_b\right) + PI$$

[redacted]

avg. skin temperature



core temperature



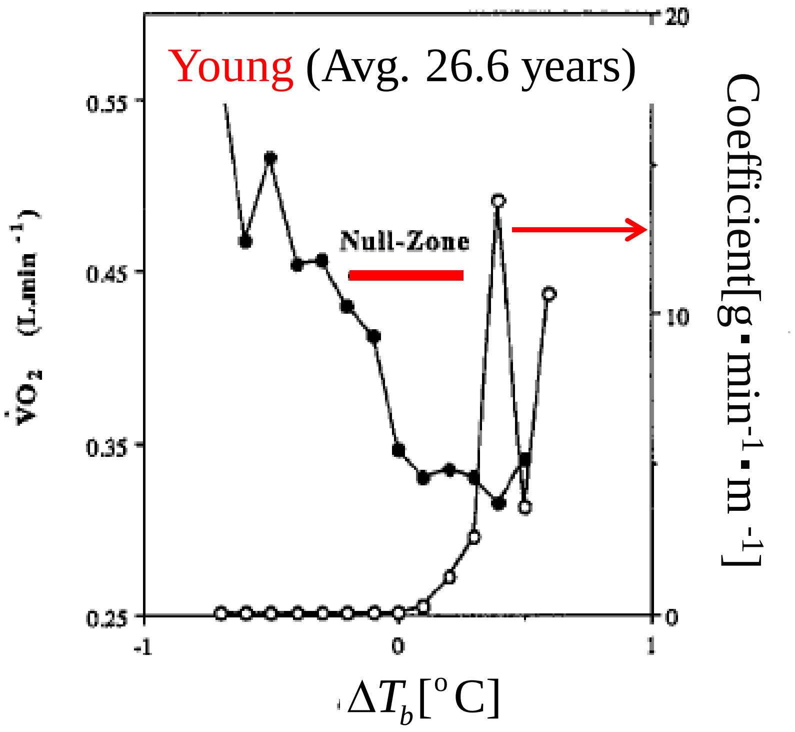
The human body is cooled down due to evaporation of sweat; this modeling is essential when investigating core temperature.

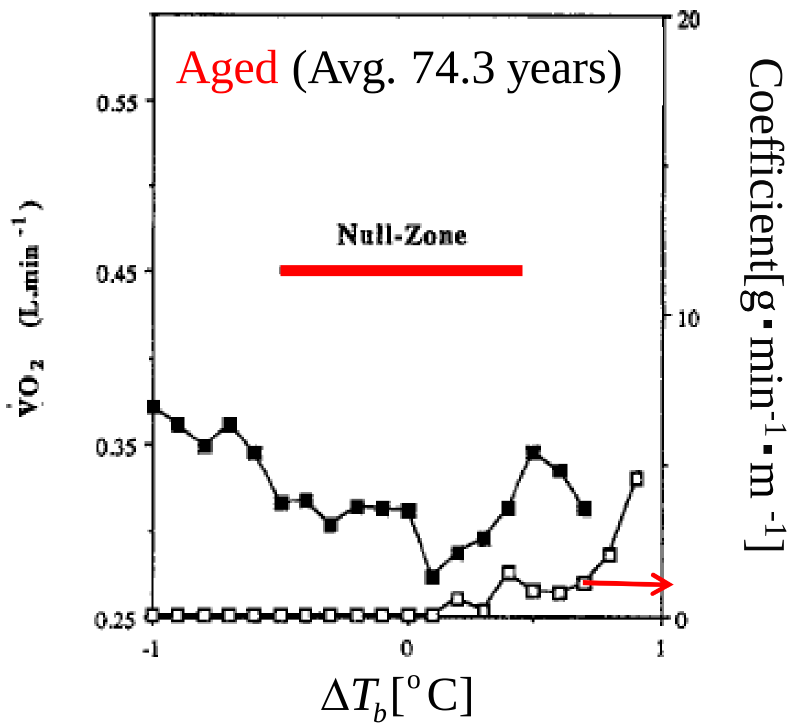
Eur J Appl Physiol (1996) 73: 278–286

ORIGINAL ARTICLE

G.S. Anderson · G.S. Meneilly · I.B. Mekjavic

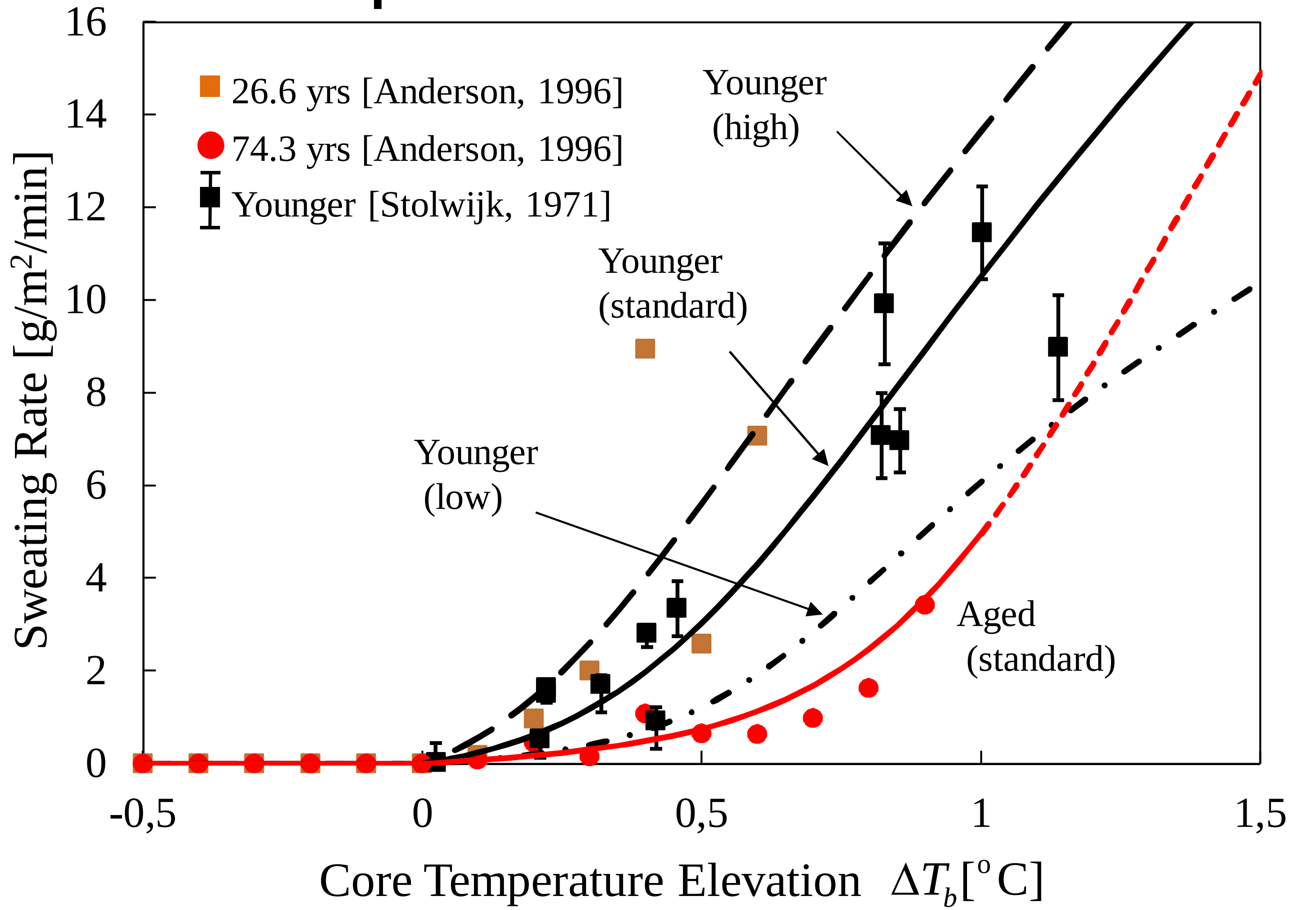
Passive temperature lability in the elderly





Thermoregulatory mechanism does not work for small core temperature change in the aged.

Dependence of Sweating Rate on Core Temperature Elevation



Sensitivity of core temperature elevation in the aged is declined by 0.6 ± 0.2 °C.

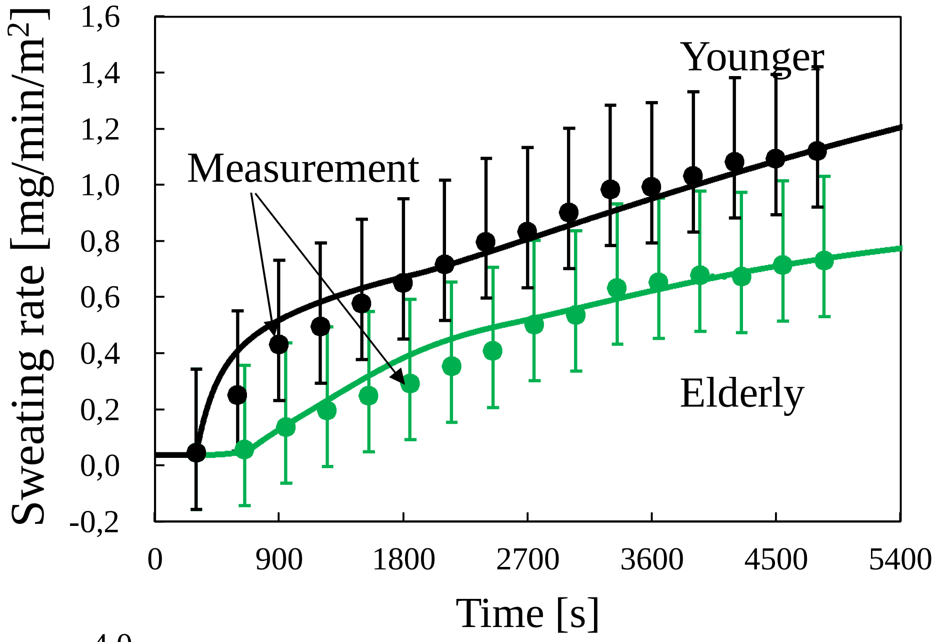
[redacted]

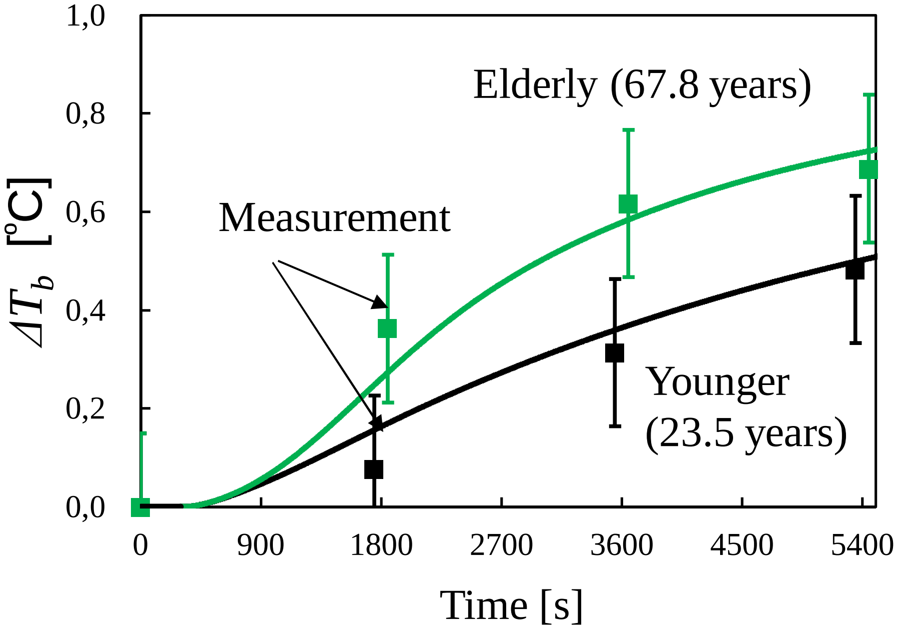
Validation (1)

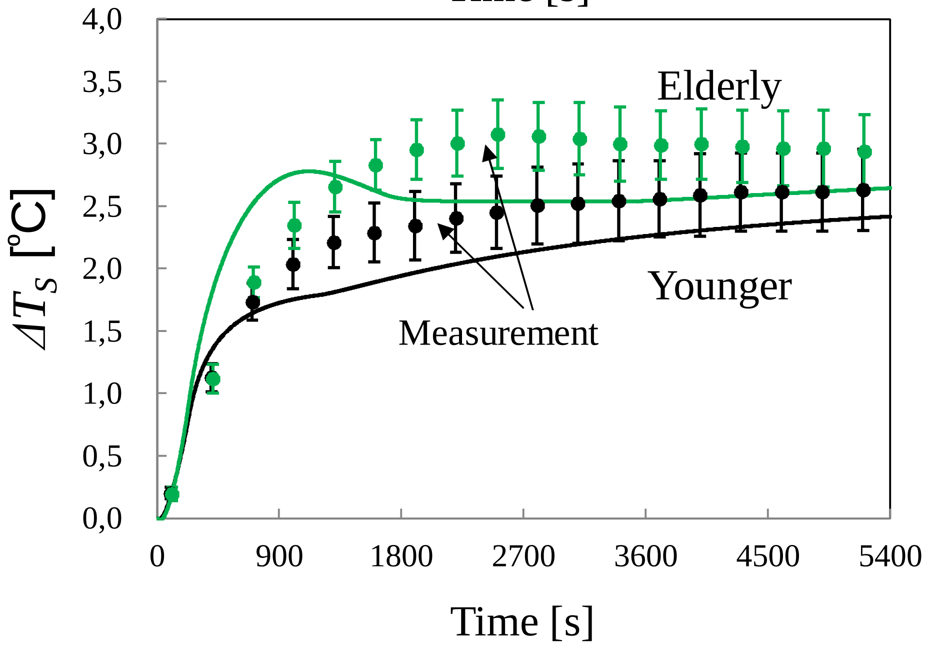
1) A thermoneutral room with air and wall temperatures of 28 °C
2) An ambient temperature was changed from 28 to 40 °C in the first 4 min and then remained at 40 °C for 86 min.

The decline in the thermoregulatory signal (~1.5 °C) from the skin (decline of skin sensitivity) is observed in the elderly.

[redacted]







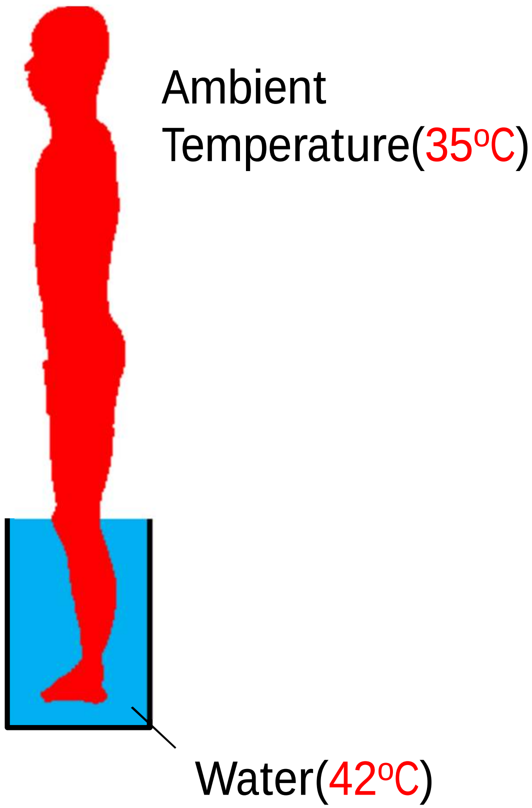
Decline of sweating starts around 40 years.

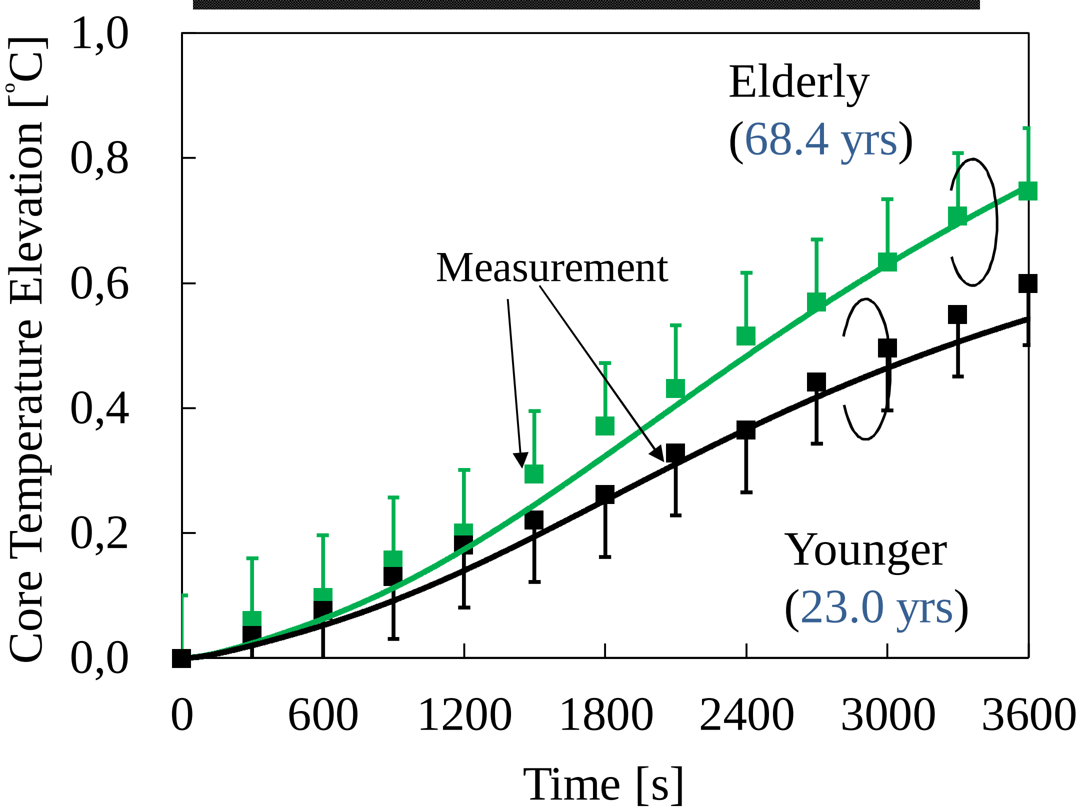
[redacted]

Validation (2)

1) ambient temperature of 28 °C and relative humidity of 45%;
2) ambient temperature of 35 °C, and sat on a chair
3) the subject immersed his legs to the knees into a stirred water bath maintained at 42 °C for 60 min.
4) The mean age for the elderly and younger were 68.4 years and 23.0 years.

[redacted]

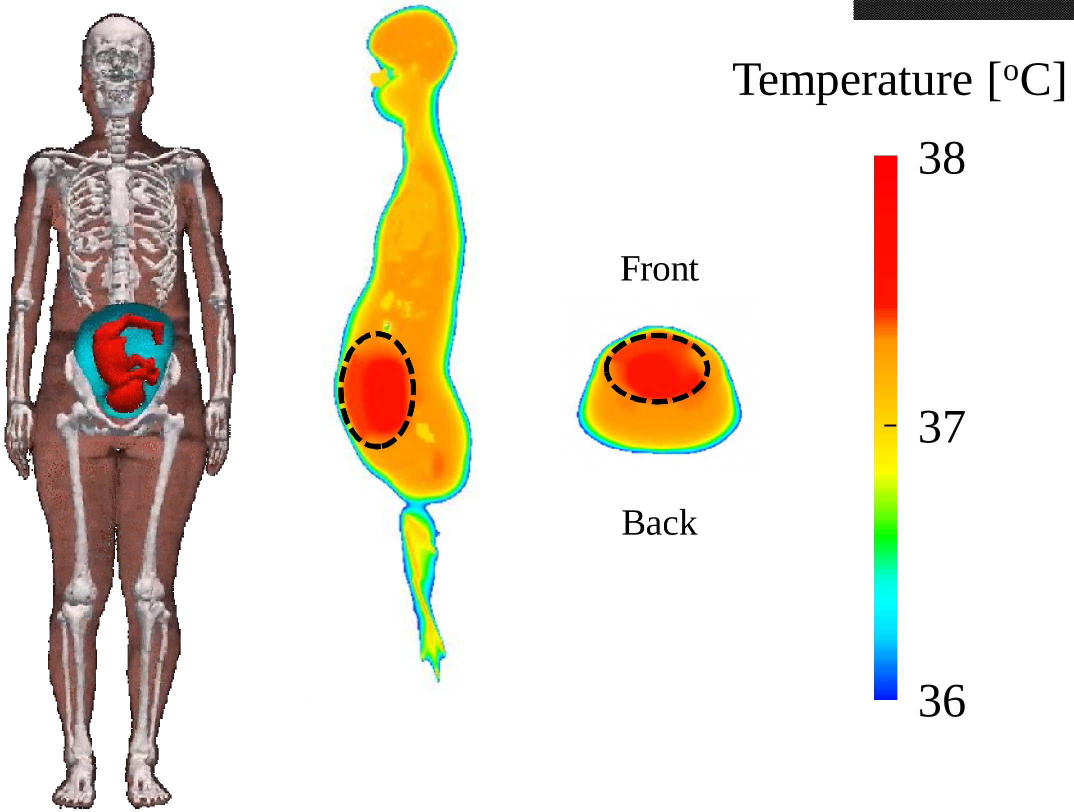




[redacted]

Thermal Modeling of Fetus and Mother

[redacted]



The temperature in the foetus has been reported to be 0.3−0.5 °C higher than that in the mother in the thermoneutral condition.

The heat exchange in the placenta was considered so that the maternal and foetal blood circulate simultaneously in the placenta.

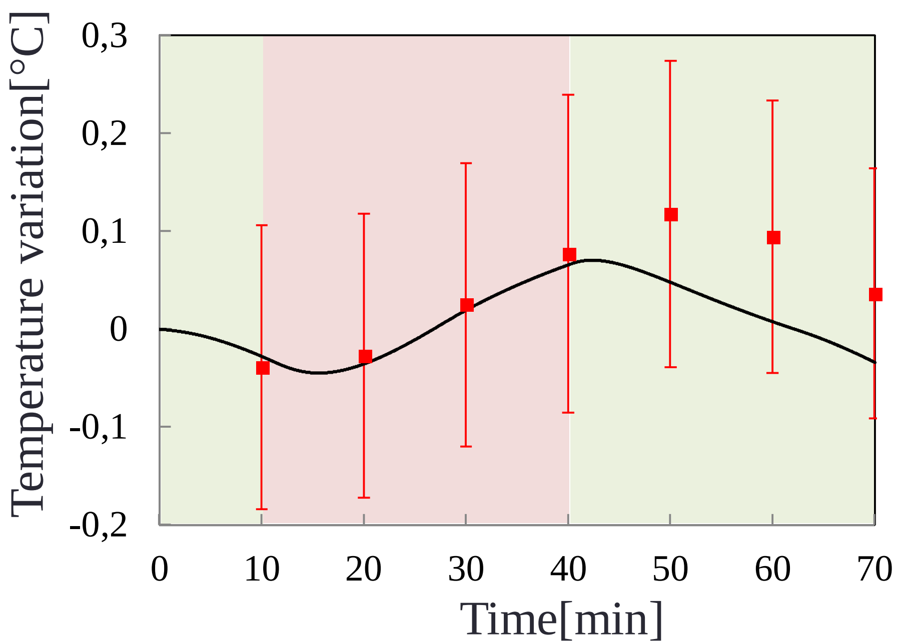
[redacted]

Thermal Modeling of Infant (8 months)

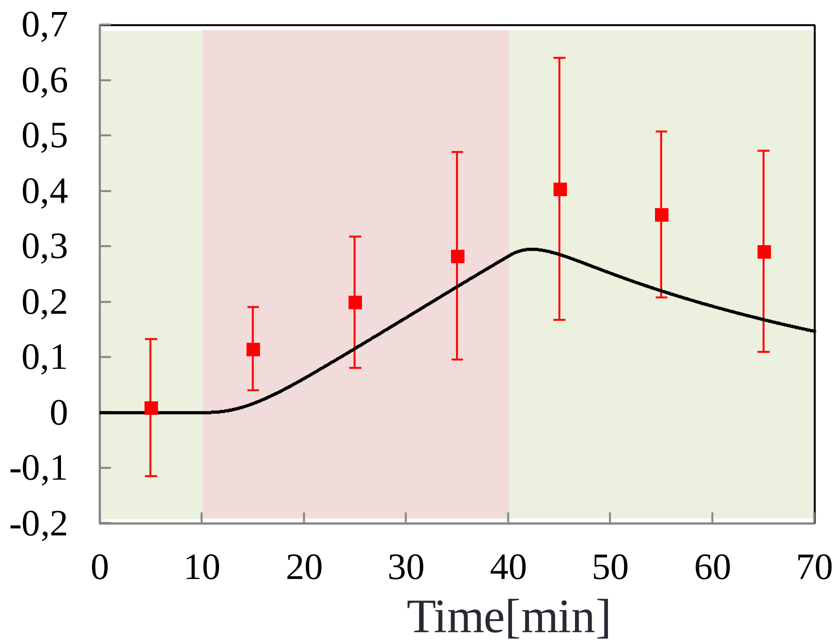
1) 0-10 min & 40-70 min.
ambient temperature of 28 °C and relative humidity of 50%;
2) 10-40 min.
ambient temperature of 35 °C and relative humidity of 70%, and sat on a chair.

[redacted]

Mother (30.8 ± 3.1 years)



Infant (7.7 ± 2.1 months)



[redacted]

Summary of Thermoregulatory Response of Humans for Ambient Heat Exposure

Using thermal computational modeling with anatomically based model, the thermoregulatory response for different ages was estimated:

1. In the elderly (approx. over 65 yrs), the thermal sensitivity in the skin is declined; 1.5 ^{o}C.
2. In the aged (approx. over 75 yrs), the thermal sensitivity in the body core (hypothalamus) is declined; 0.6 ^{o}C, in addition to the decline of heat sensitivity of the skin.
3. In the children, no clear difference was observed with adults at least for modest ambient heat load; dominant factor is the body shape (surface are-to-mass ratio).
4. In the pregnant woman, no clear difference was observed with adult female except for having a fetus with high basal metabolism.

Whole-body Exposure and Core Temperature Elevation

Validation: Back exposure at 100 MHz (45 min)

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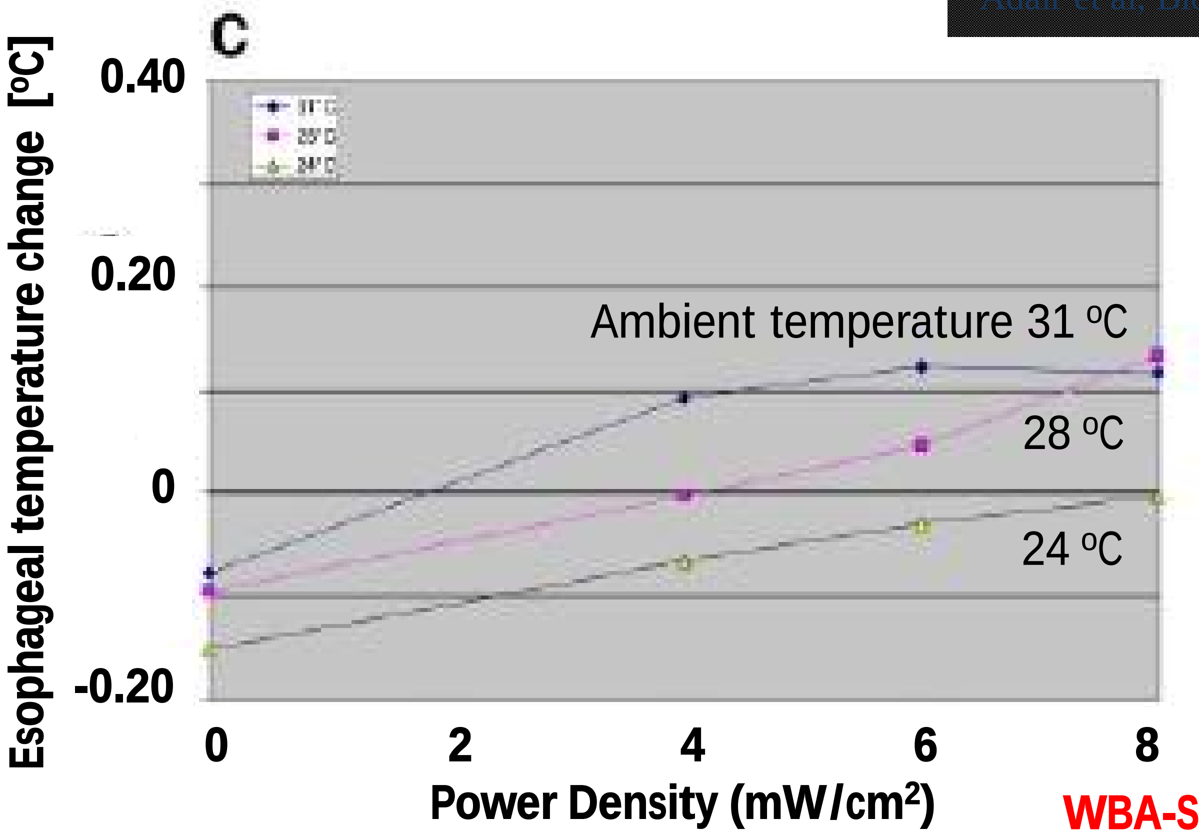
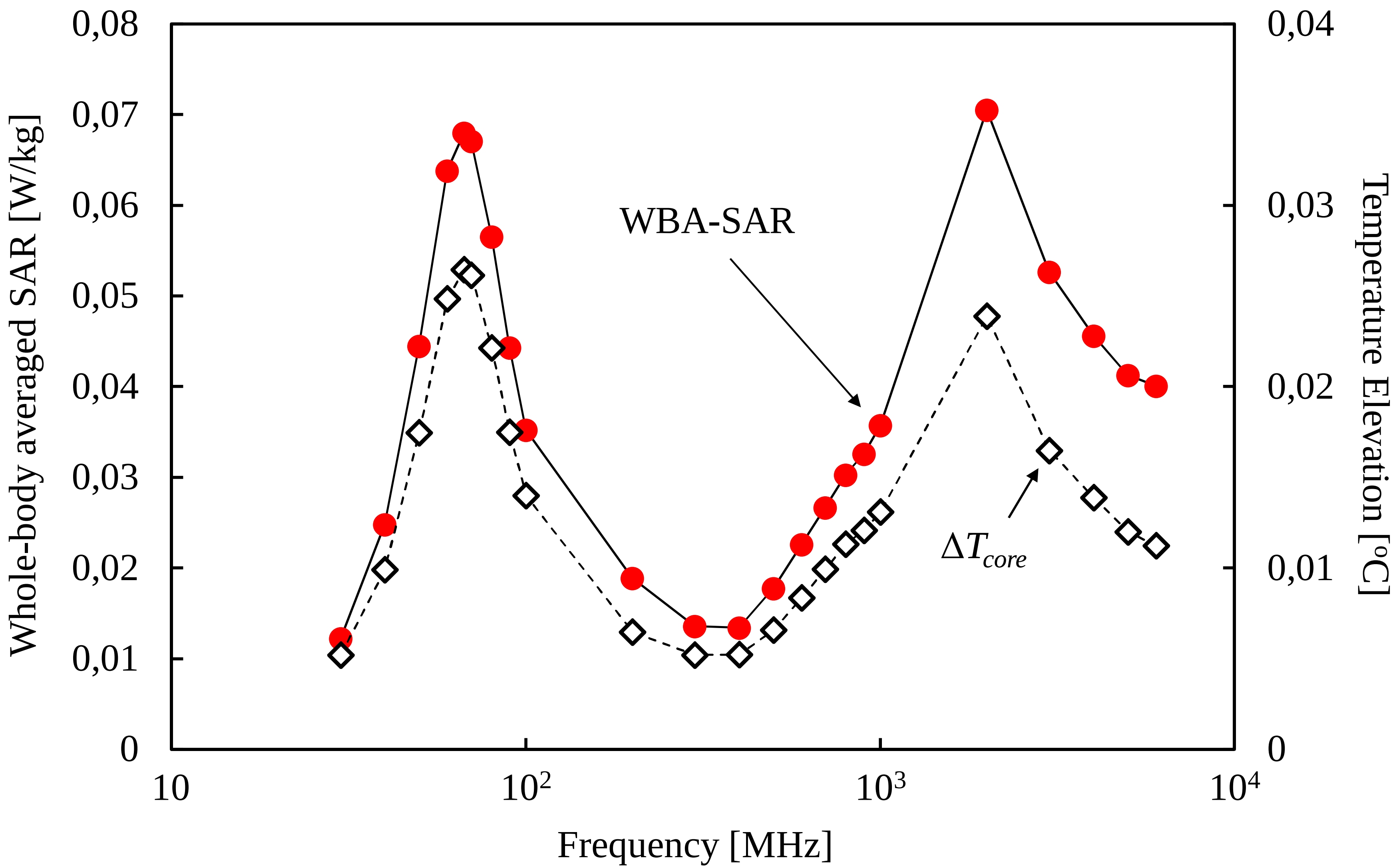


WBA-SAR
0.544 W/kg

For WBA-SAR at 0.55 W/kg for duration of 45 min.
Measured ΔT = 0.15-0.20 ºC
Computed ΔT = 0.177 ºC (65 MHz)

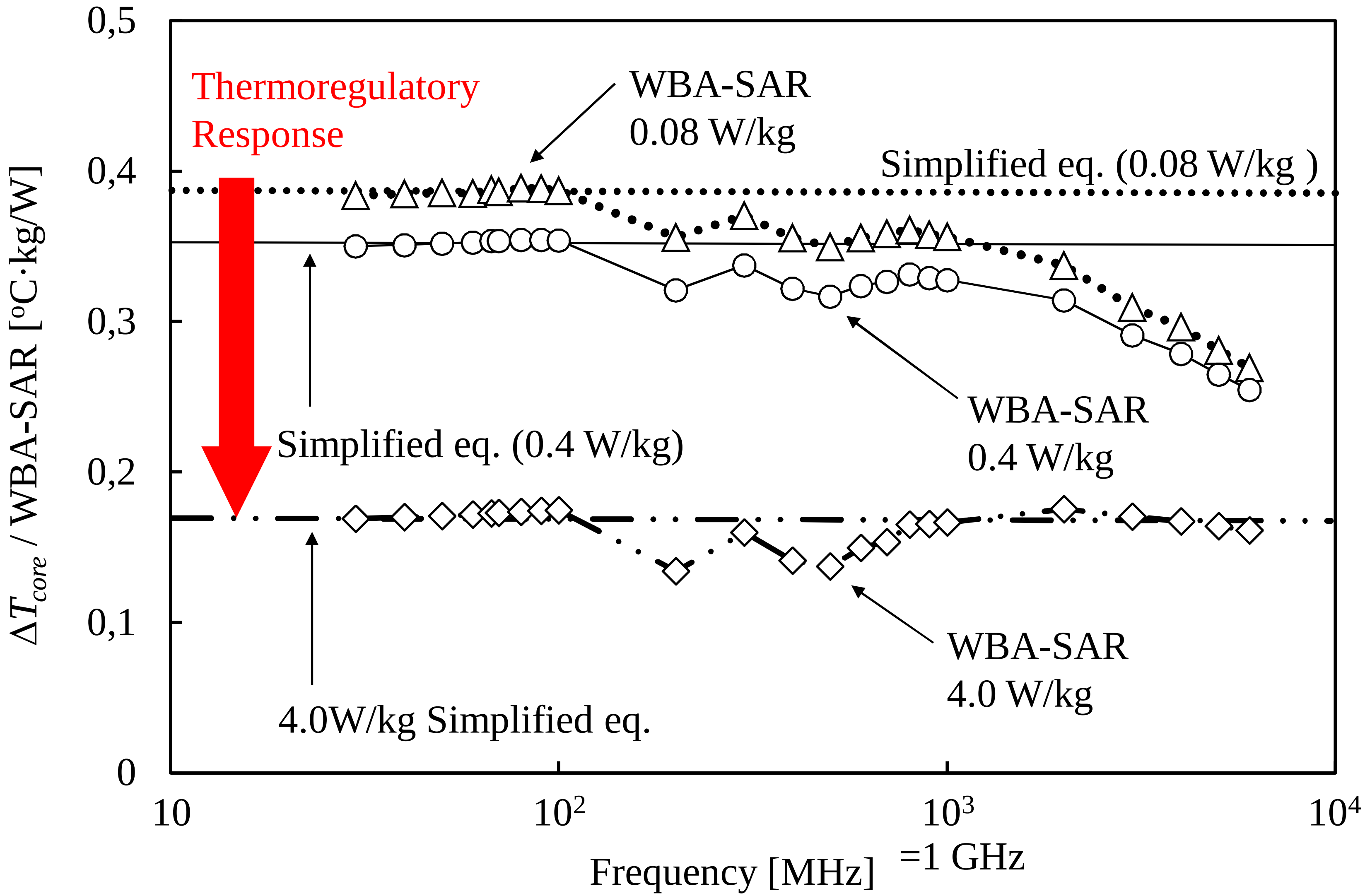
[redacted]

WBA-SAR and Core Temperature Elevation



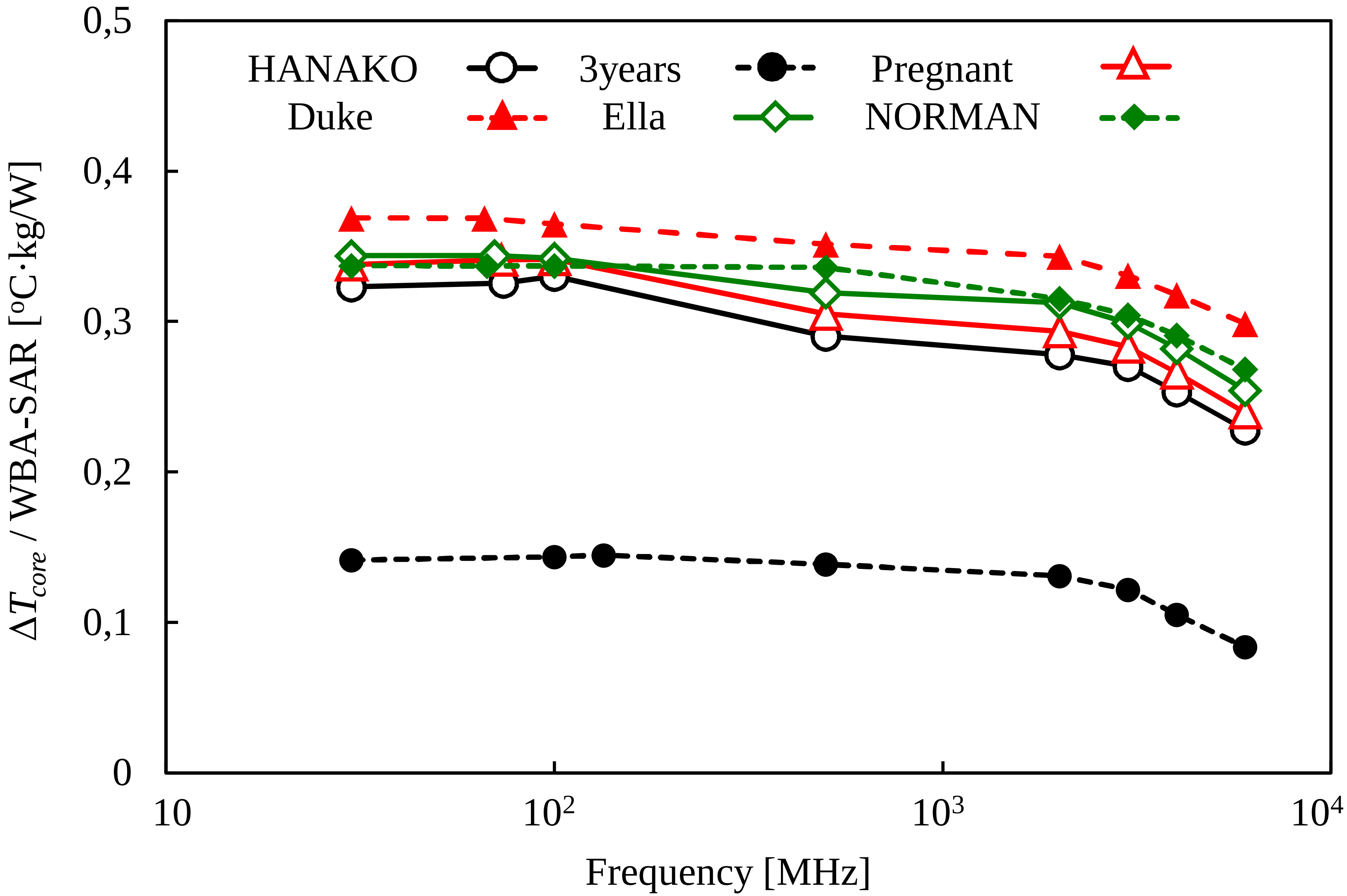
[redacted]

Core Temperature Elevation Normalized by WBA-SAR



[redacted]

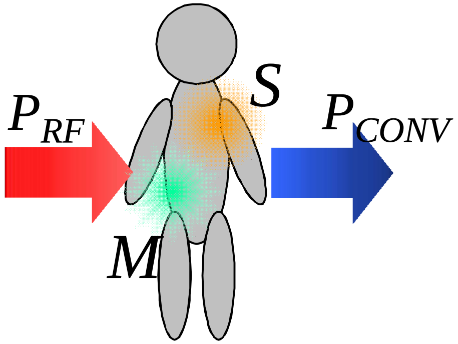
Core Temperature Elevation Normalized by WBA-SAR of 0.4 W/kg



[redacted]

Dominant Factor Affecting Core Temperature Elevation

[redacted]



$$M + P_{RF} - P_{CONV} = S$$

M : Basal Metabolism

P_{RF} : RF power Absorption

P_{CONV} : Heat Convection to Air

S : Power stored in Human

Derived Formula

$$T(t) = T_0 + \frac{W \cdot SAR_{WBave}}{\int_S H(\vec{r})dS + \int_S sw(t)dS}\left(1 - \varepsilon^{-\frac{\int_S H(\vec{r})dS + \int_S sw(t)dS}{W \cdot C_{WBave}}t}\right)$$

W : Model Weight [kg]

H : Heat Transfer Coefficent [W/m²・°C]

SAR_{WBave} : WBA-SAR[W/kg]

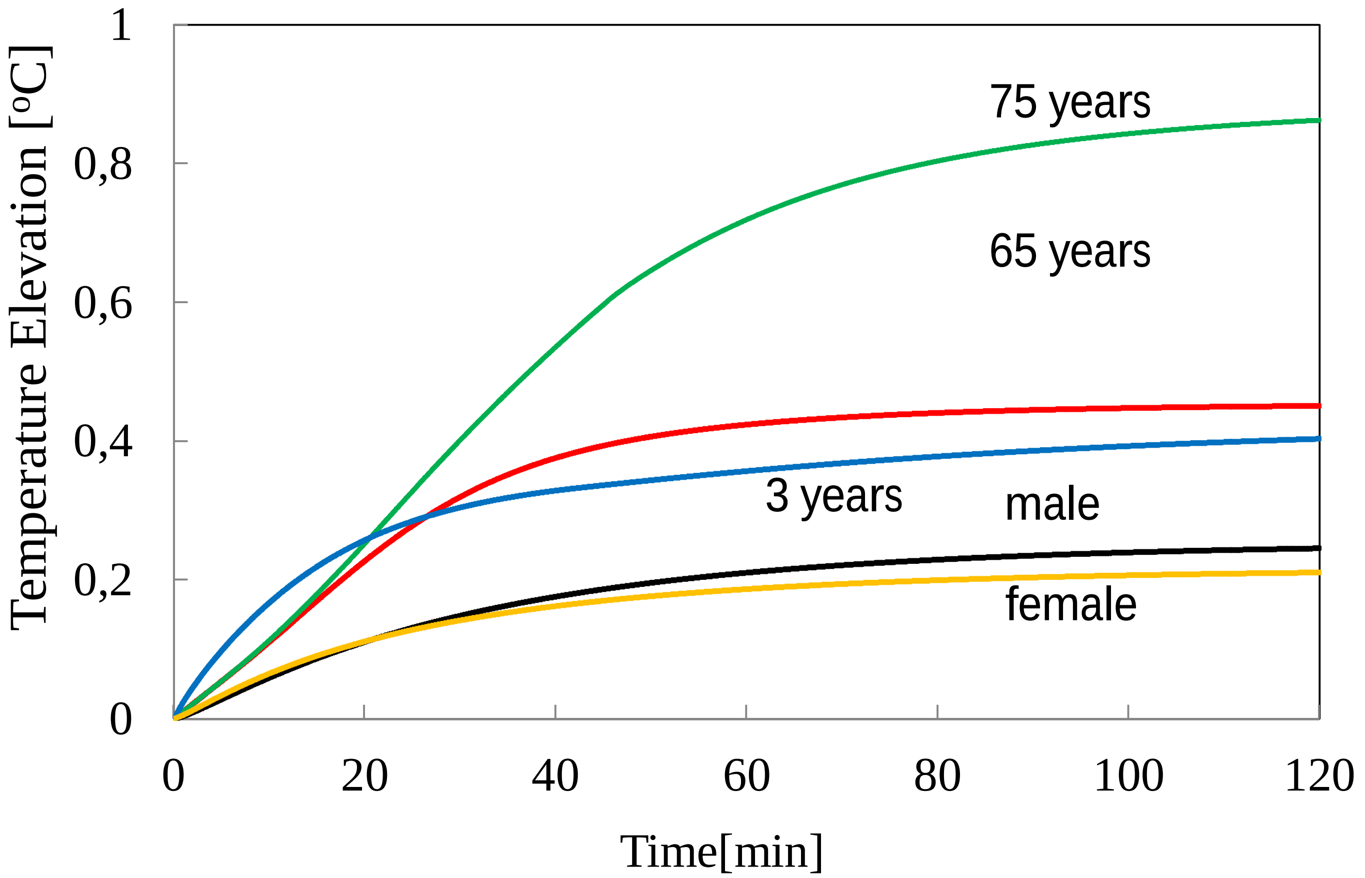
C_{WBave} : Specific Heat Averaged Over Body [J/kg・°C]

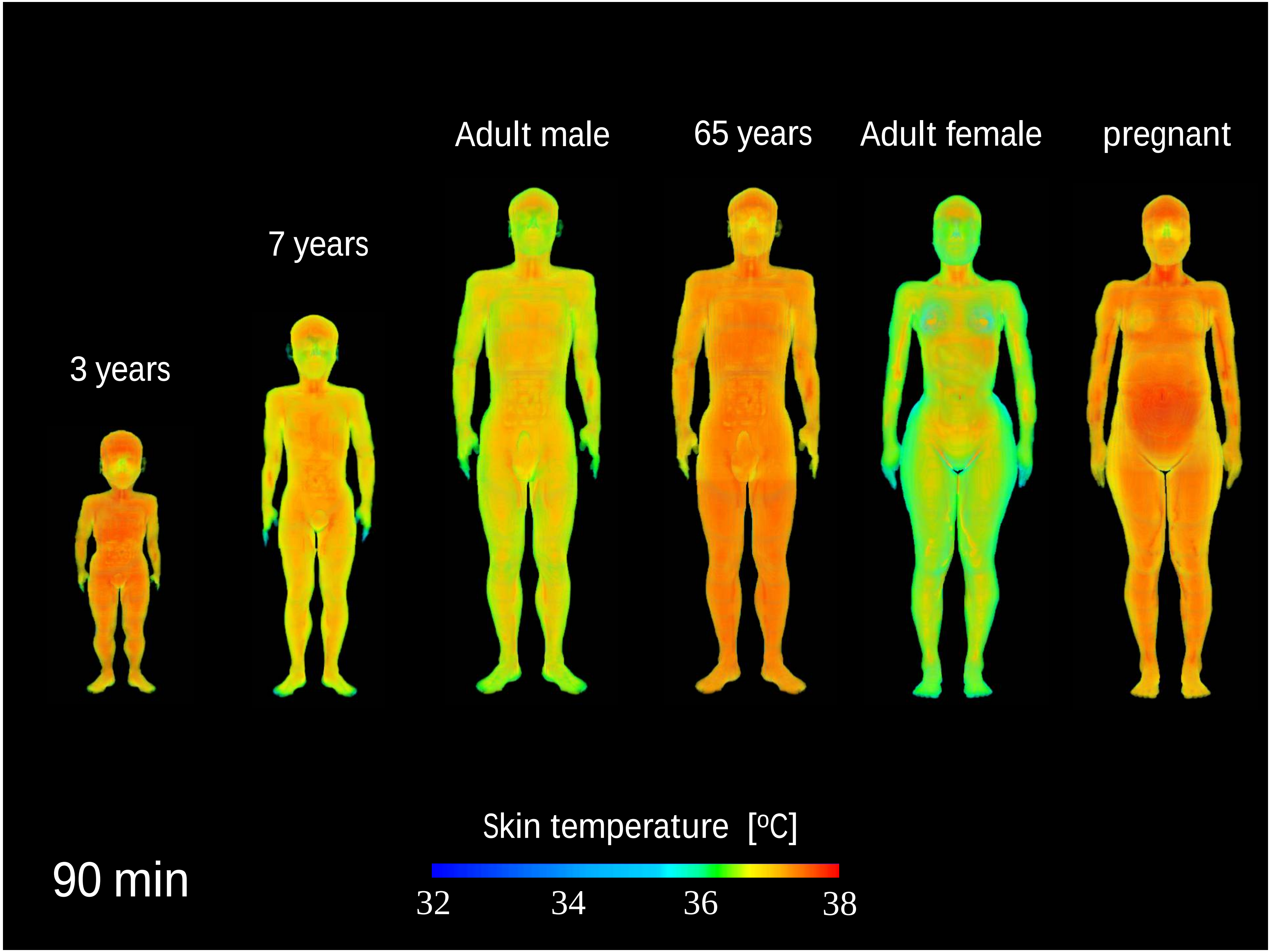
sw : Perspiration Coefficient[W/m²・°C]

A. Hirata et al., *Prog. In Electromag. Res.*, vol.99, pp.53-70, 2009.

Comparison of core temperature elevations between RF and ambient heat exposures

Core Temperature Elevations for ambient temperature of 35 ^oC and humidity of 60% (1 hour)

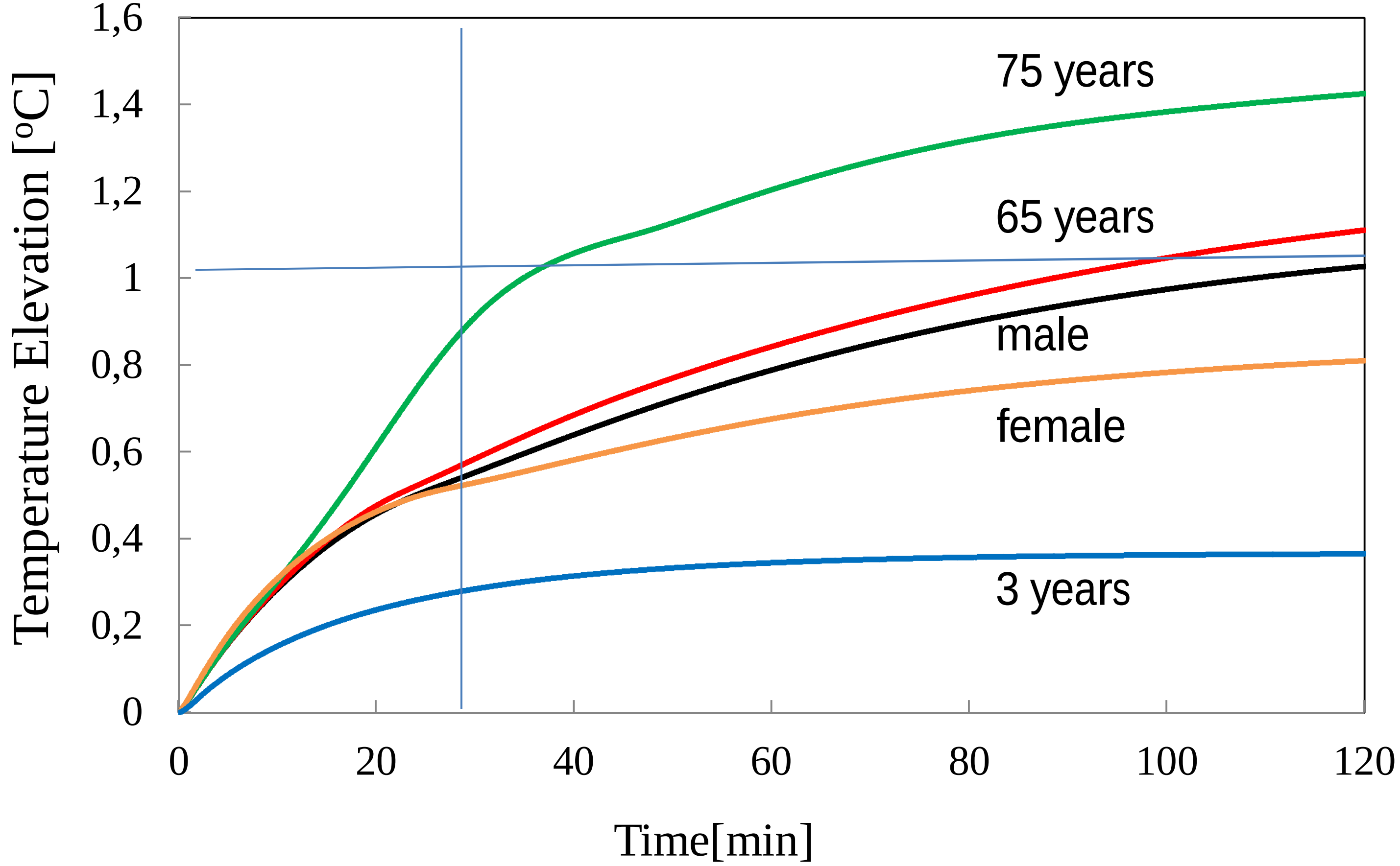




Adult male
65 years
Adult female
pregnant
7 years
3 years
Skin temperature [°C]
90 min
32
34
36
38

Core Temperature Elevations at WBA-SAR of 4 W/kg (10 times as large as the limit of 0.4 W/kg)

[redacted]



Thermal time constant of body core is 20 min. or longer (WBA-SAR).

Summary of ΔT_{core} to WBA-SAR

1. Core temperature elevation in the aged at WBASAR of 4 W/kg is 0.9 ^{o}C at 30 min (ACGIH 1.0−1.5 ^{o}C (heat adapted), ISO 1.0 ^{o}C).
2. Core temperature elevation in the child is smaller than that in the adult due to higher body-surface-area-to-mass ratio.
3. Core temperature elevation in the elderly is higher than that in the adult due to lowered sweating rate.
4. Comment on Shellock MRI papers: ambient temperature is low.

ACGIH (2012) Heat Stress and Strain TLV@ACGIH: American Conference of Governmental Industrial Hygienists. Cincinnati.
ISO9886 (2004)Ergonomics of the thermal environment：Evaluation of thermal strain by physiological measurements. Geneva

Thermoregulation during exercise in the heat in children: old concepts revisited

Thomas Rowland

Journal of Applied Physiology Published 1 August 2008 **Vol.** 105 **no.** 2, 718-724 **DOI:** 10.1152/japplphysiol.01196.2007

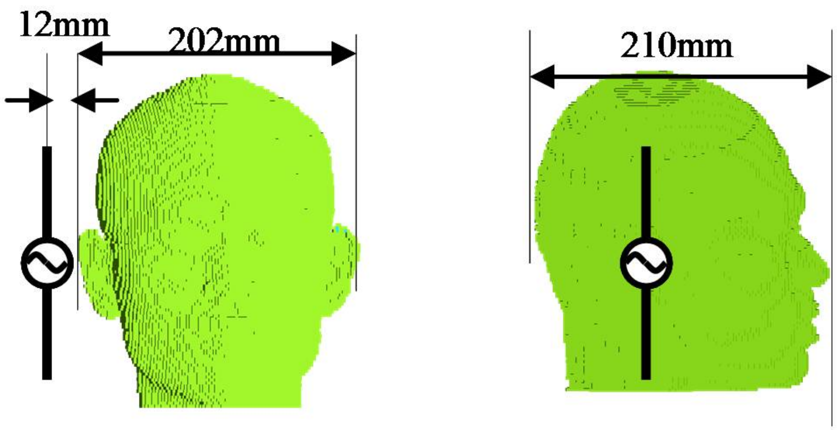
Children possess certain physiological and anatomic characteristics that have traditionally been considered to impair thermoregulatory responses to exercise in the heat.

....

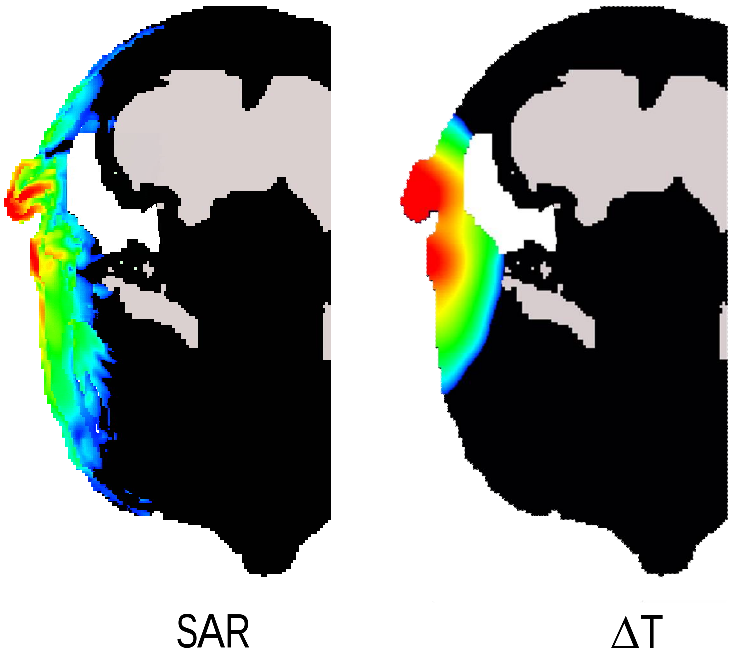
These findings imply that no maturational differences exist in thermal balance or endurance performance during exercise in the heat, nor that child athletes are more vulnerable to heat injury.

Localized Exposure and Averaging Mass of SAR

Anatomically-based Head Model



- ◆Wang and Fujiwara (IEEE MTT,1999)
- ◆Leeuwen et al.(Phys.Med.Biol.1999)
- ◆Bernardi et al. (IEEE MTT, 2000)
- ◆Wainwright(Phys.Bio.Med.2000)
- ◆Gandhi et al. (IEEE MTT, 2001)
- ◆Hirata et al. (IEEE EMC, 2003)
- ◆Samaras et al. (IEEE EMC, 2007)

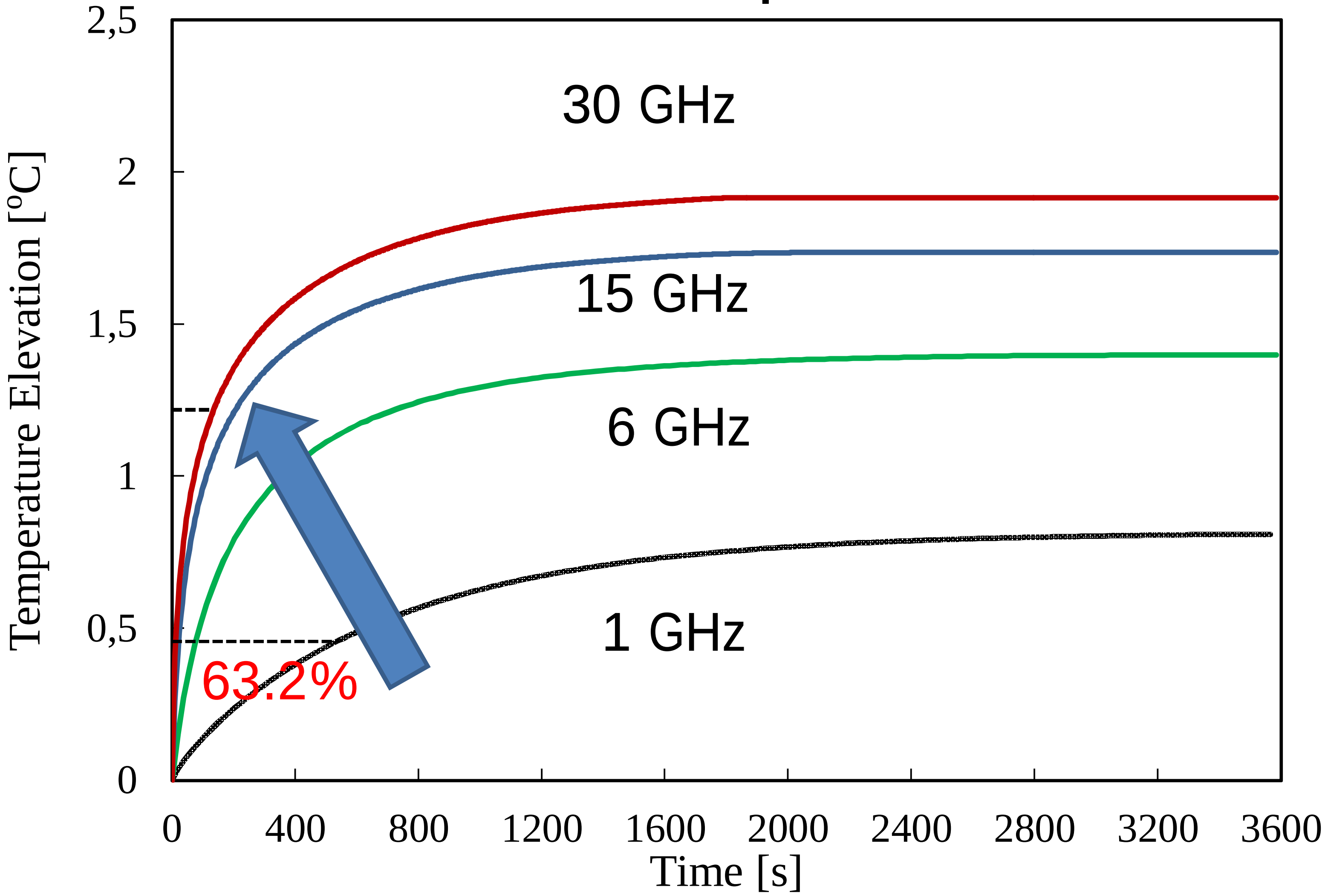


Temperature elevation distribution in the human model is smoother than that of SAR due to heat diffusion.

Frequency=6 GHz

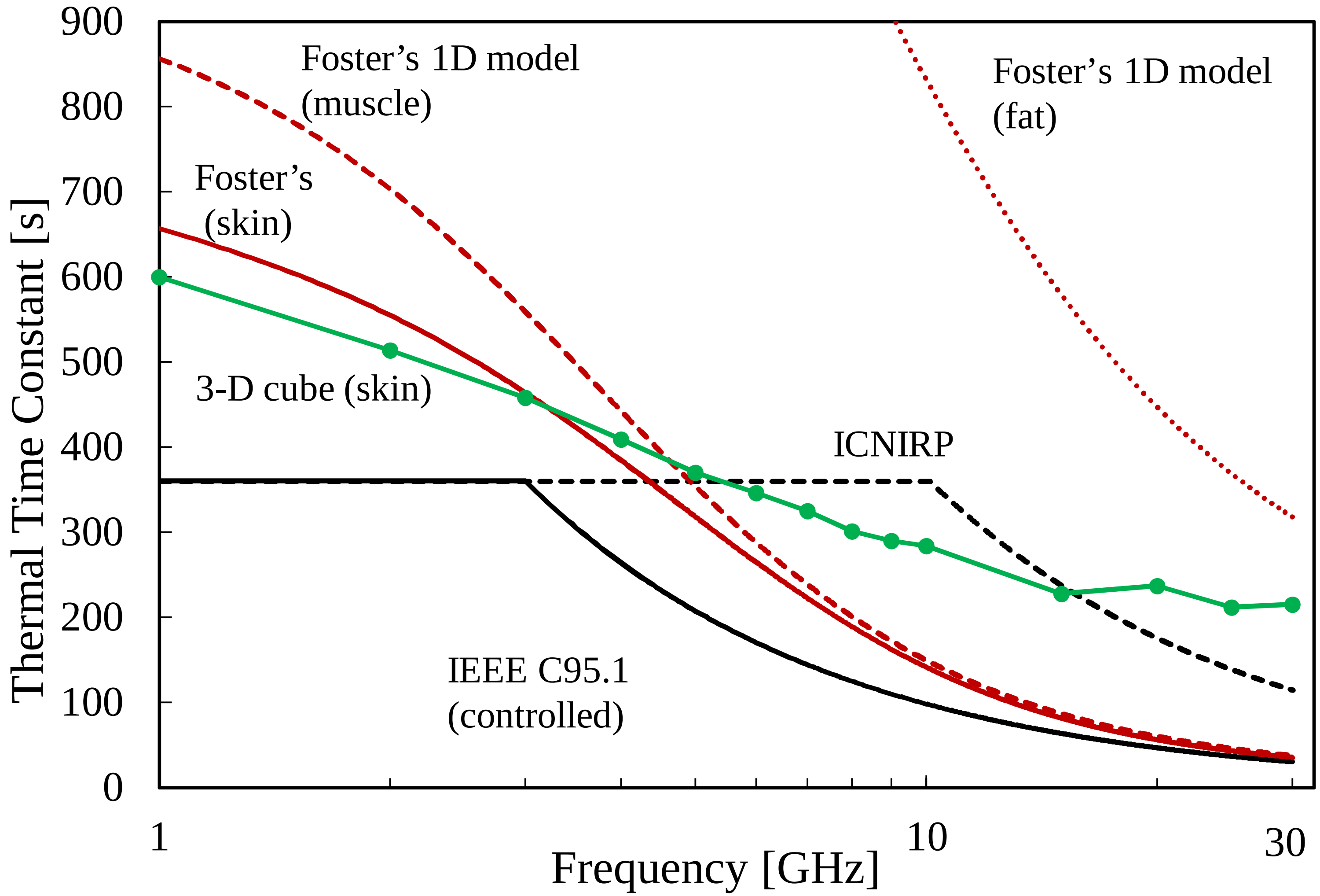
Thermal steady state (~30 min)

Definition of Thermal Time Constant at antenna output of 1 W



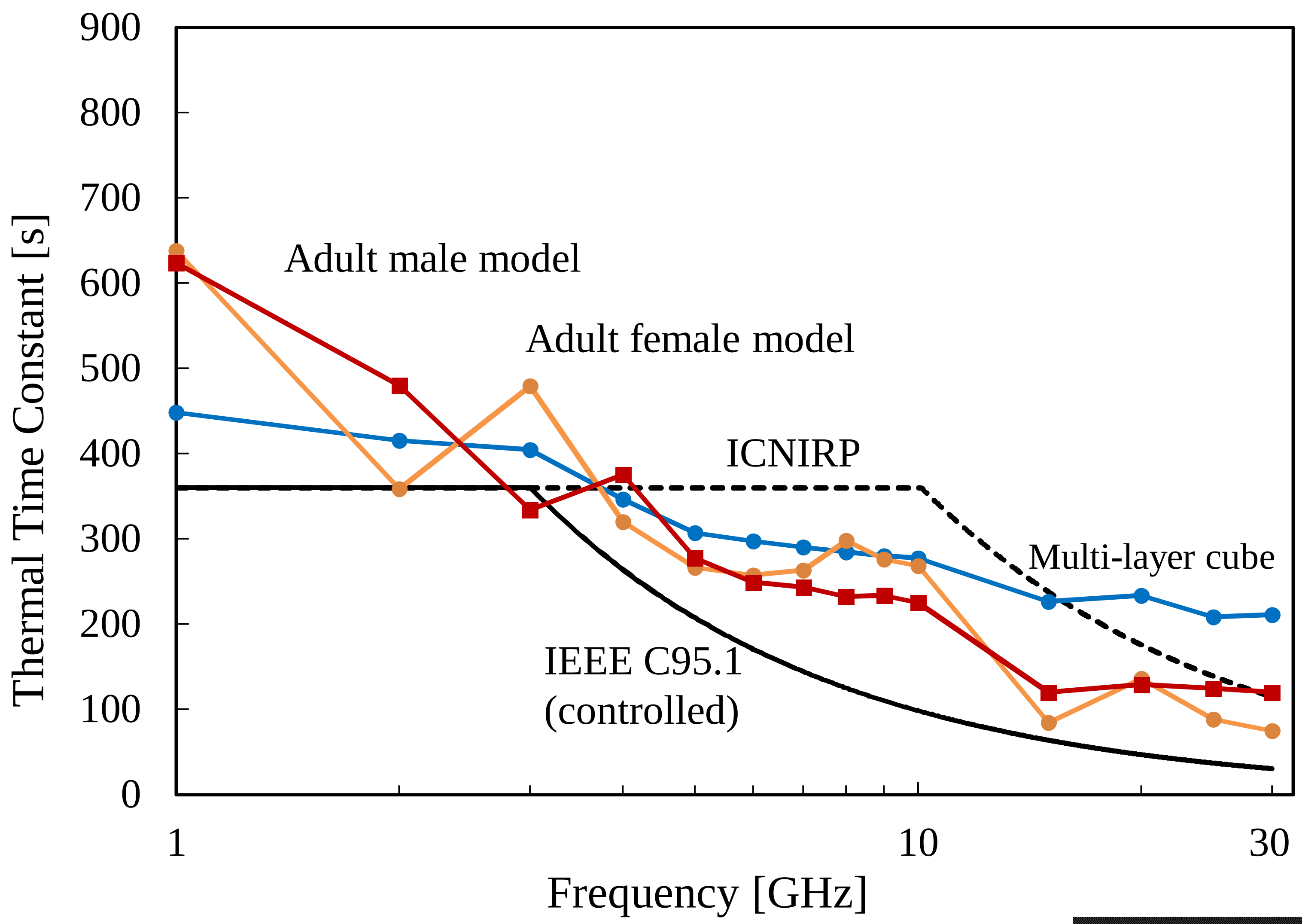
Thermal Time Constant in Simplified Model

[redacted]



[redacted]

Thermal Time Constant in 3-D Human Heads



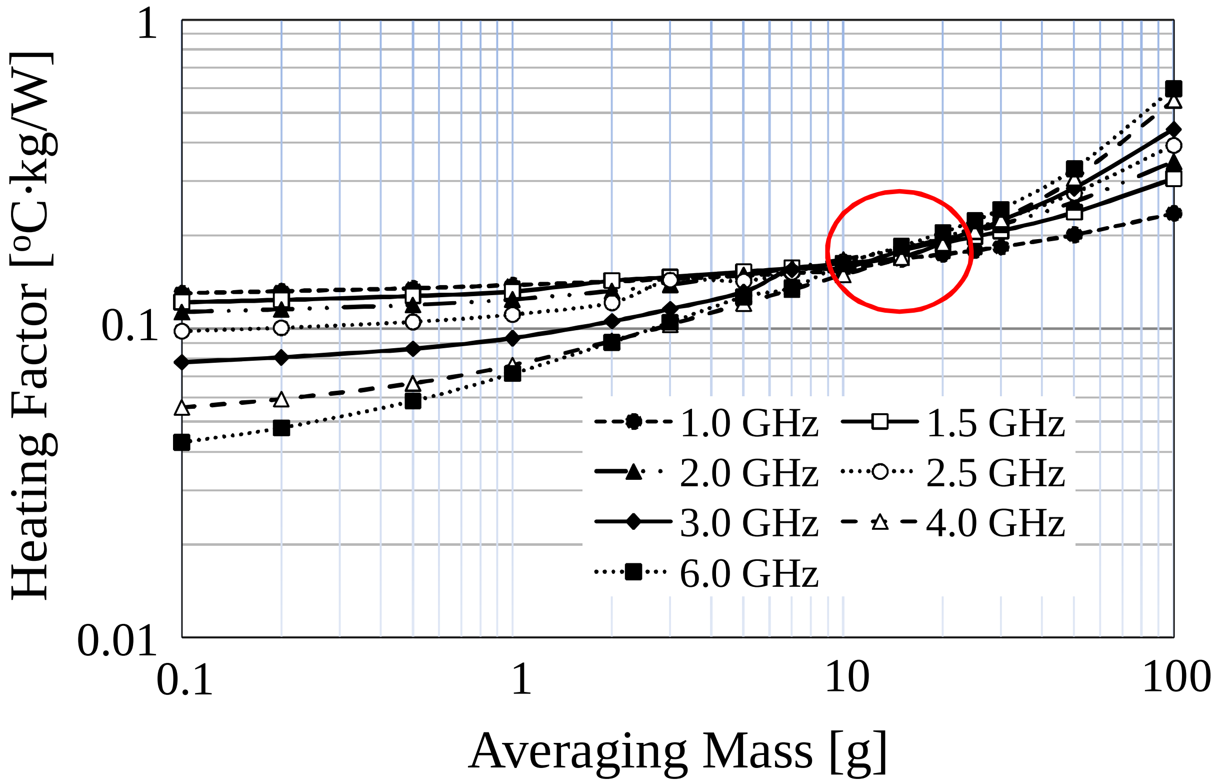
[redacted]

Post processing of Computational Results

- Heating factor is defined as $\Delta T/SAR_{avg}$.
- The method of least square is used for all voxels of ΔT/SAR, which is larger than 1/100 of the maximum value.
- Coefficient of determination represents the square of correlation coefficient. The closer to unity the coefficient of determination is, the better the correlation is.

Hirata et al., Prog. In Electromagnet. Res. 84 221-37, 2008.
Razmadze et al., Electromagnet., 27, 77-90, 2009.
Hirata and Fujiwara, Phys. Med. Biol., 2009.
McIntosh and Anderson, Bioelectromagnet., 31, 467-478, 2010.

Effect of Averaging Mass-averaged SAR to Temperature Elevation (NITech head model)



The heating factors converge at the averaging mass of 8-20 g.

ΔT can be estimated in terms of SAR at different frequencies.

[redacted]

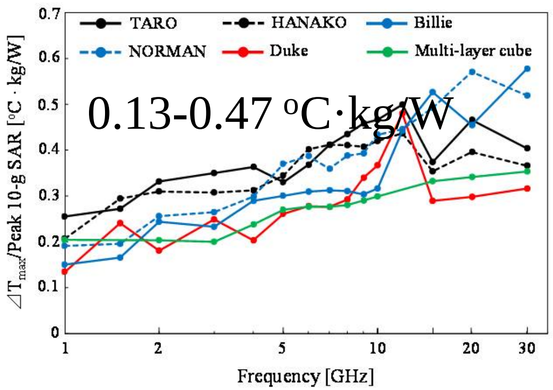
Heating Factor of peak ΔT to peak 10g SAR for Different SAR Averaging Algorithms

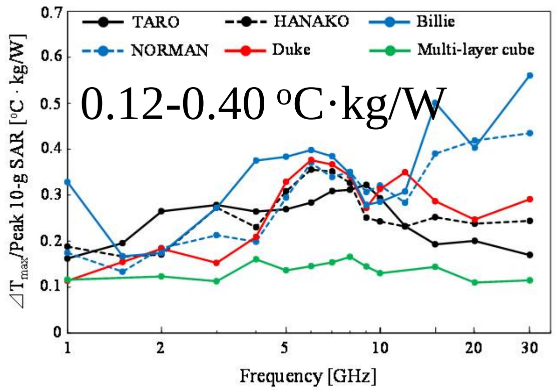
Cube

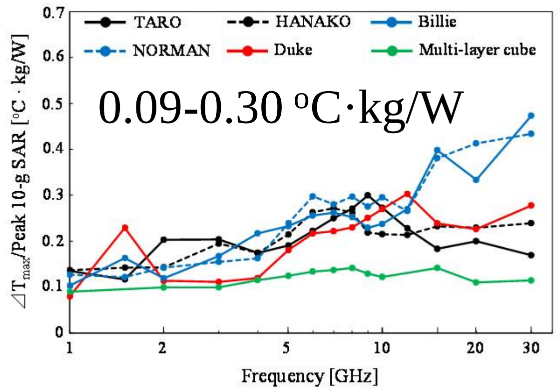
Single tissue contiguous

Multiple tissue contiguous

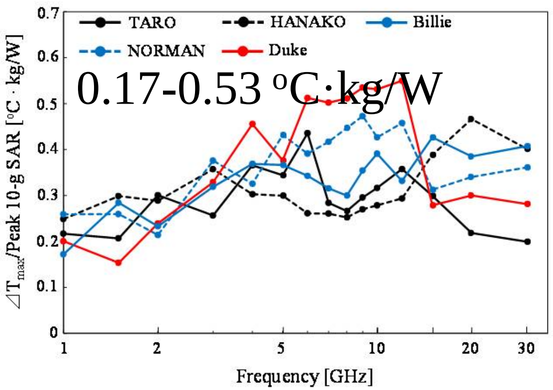
w/o pinna

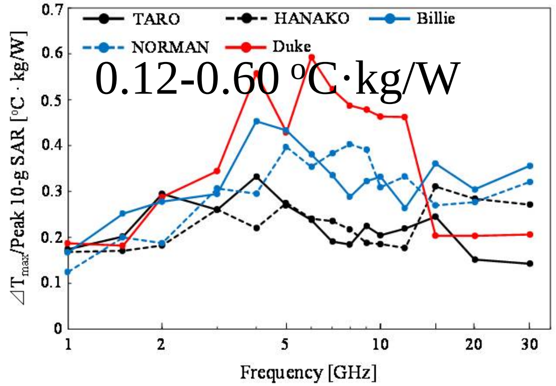


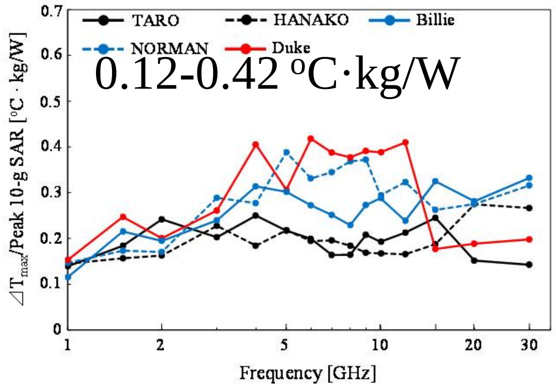




w/ pinna







[redacted]

Summary of ΔT to peak SAR

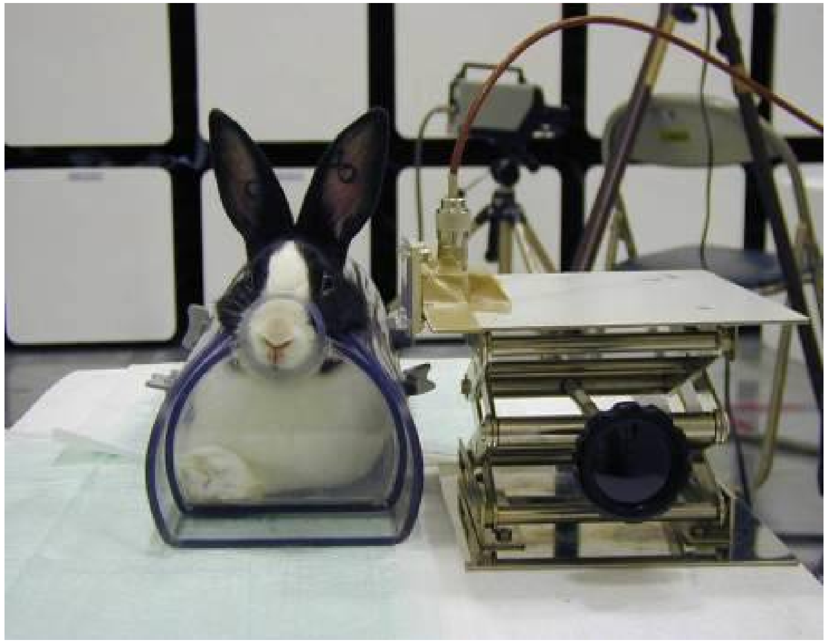
- The thermal time constant become small with the increase of the frequency as reported by Foster et al. The curves of thermal time constant and ICNIRP averaging time cross at frequency around 3-4 GHz.
- For voxels over the head, 10-g (8-20 g) averaged SAR is a good metric to estimate the temperature elevation; heat diffusion length is the order of a few centimeters (up to 6 GHz).
- From voxel-by-voxel relation between peak SAR and peak temperature elevation, the upper applicable frequencies in ICNIRP (10 GHz) and IEEE (3-6 GHz) are reasonable (depending on the averaging scheme). The effect of pinna is significant.

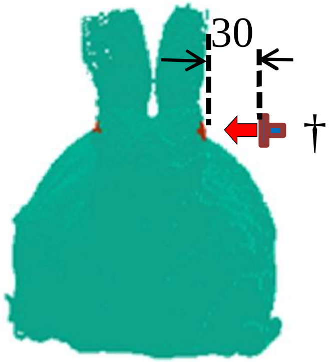
#Better averaging algorithm for frequencies up to 10 GHz is to average over multiple & contiguous tissue without the pinna .

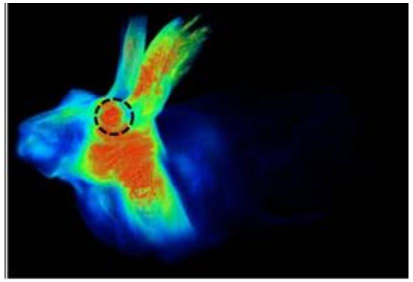
Plane-wave and Localized Exposure to Rabbit and Human Eyes

Microwave Exposure on Rabbit Eye

- Systemic anesthesia was administrated in Guy et al. [A]
- Local anesthesia to the eye only was applied in Kojima et al [B].
- Eye temperature with systemic anesthesia was larger than that without systemic anesthesia.



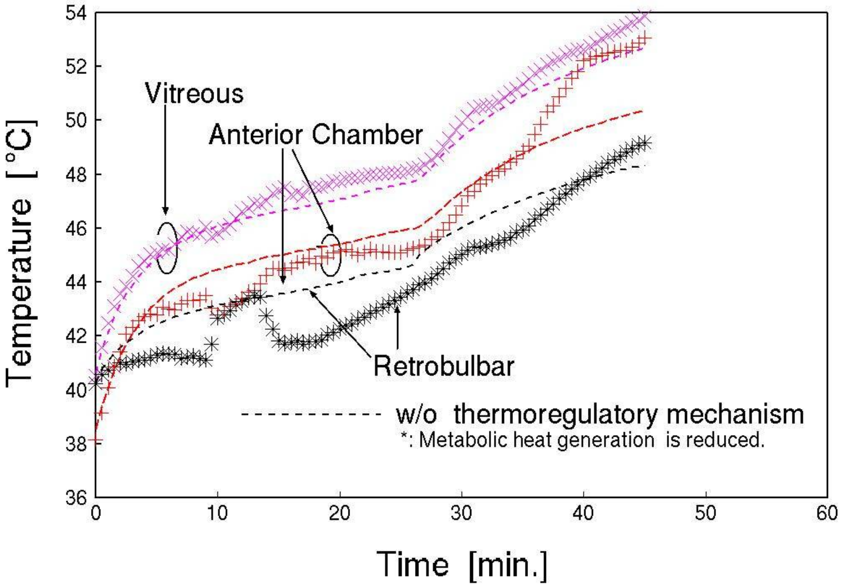




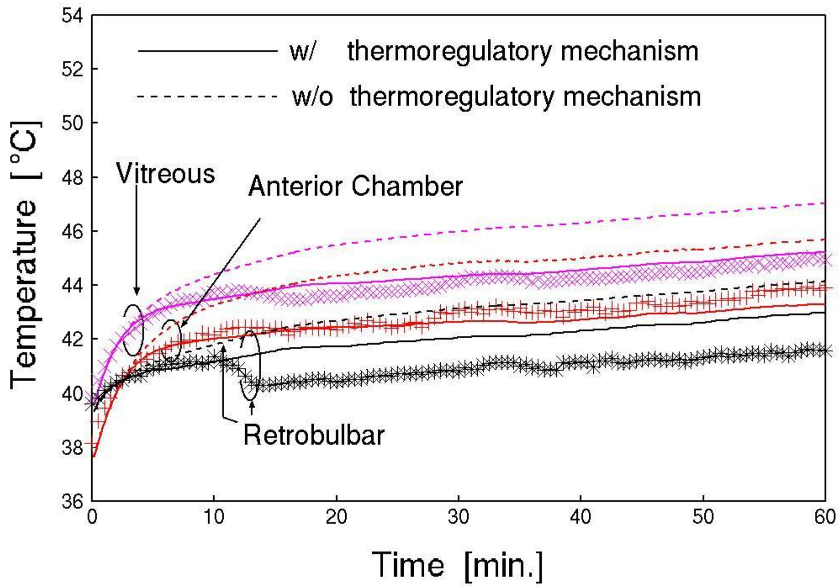
[A] A. W. Guy et al , *IEEE MTT*, 1975
[B] M. Kojima et al, *Bioelectromagnet.*, 2004

† K. Wake et al, IEEE Trans. Microwave theory & Tech, 2007.

Time Evolution of Temperature in Rabbit Eye



With Systemic Anesthesia



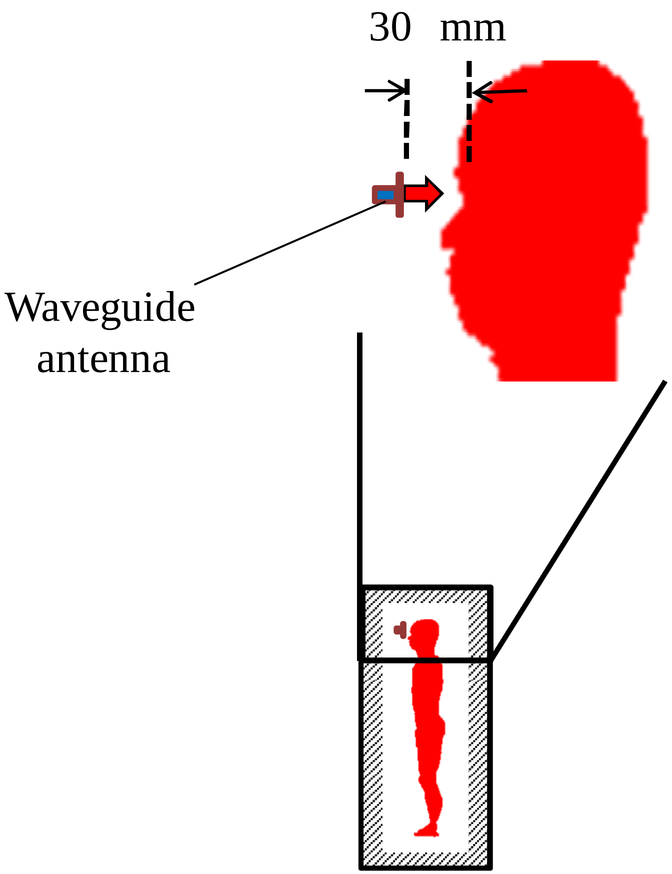
Without Systemic Anesthesia

From (a), the temperature increases steeply after the death of the rabbit (at 26 min.). Thus, the blood flow and temperature increase could be close related to each other.

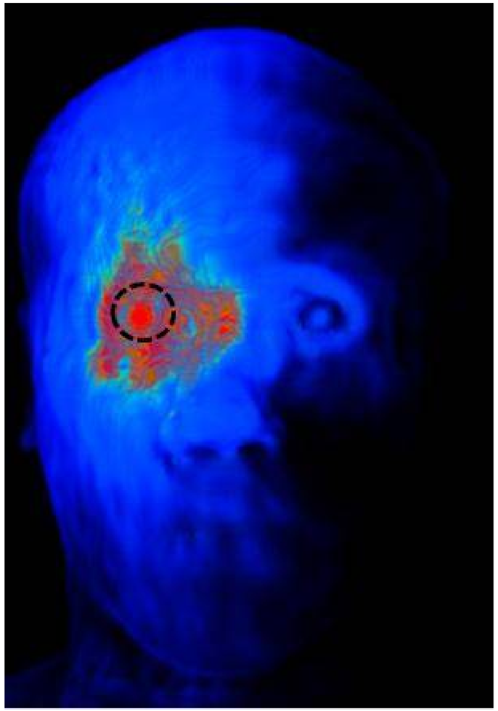
•From (b), the calculation results with the effect of thermoregulatory response considered are in good agreement with measured data without anesthesia. The calculation results without thermoregulatory response are overestimated as compared with measurements.

A. Hirata et al, *Bioelectromagnet.*, 2006

Extrapolation to human dosimetry



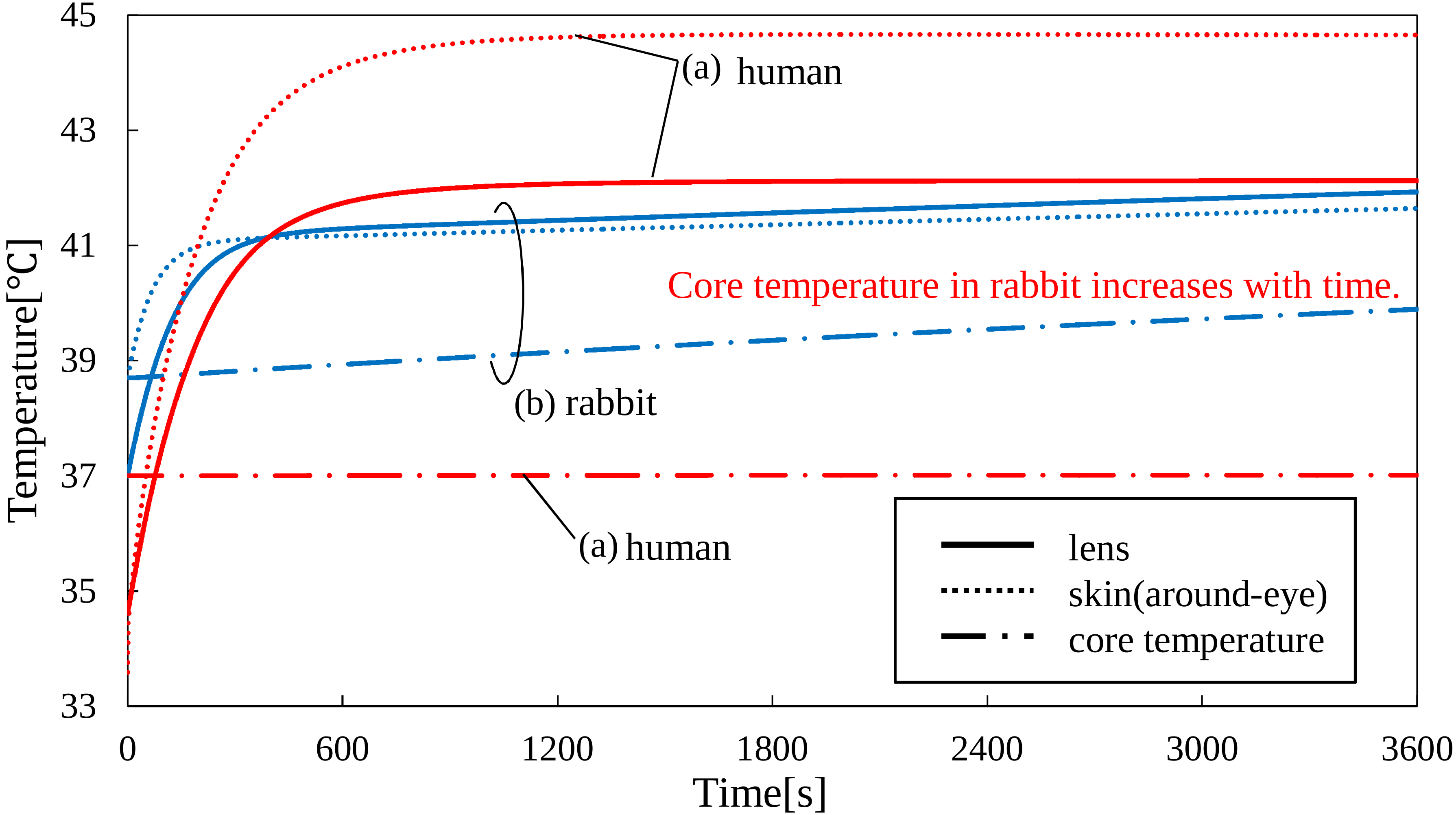
T. Oizumi et al , Radiation Prot. Dosimetry, 2013



for human thermophysiology without anesthesia, see e.g., Adibzadeh et al, *Phys. Med. Biol.*, 2015

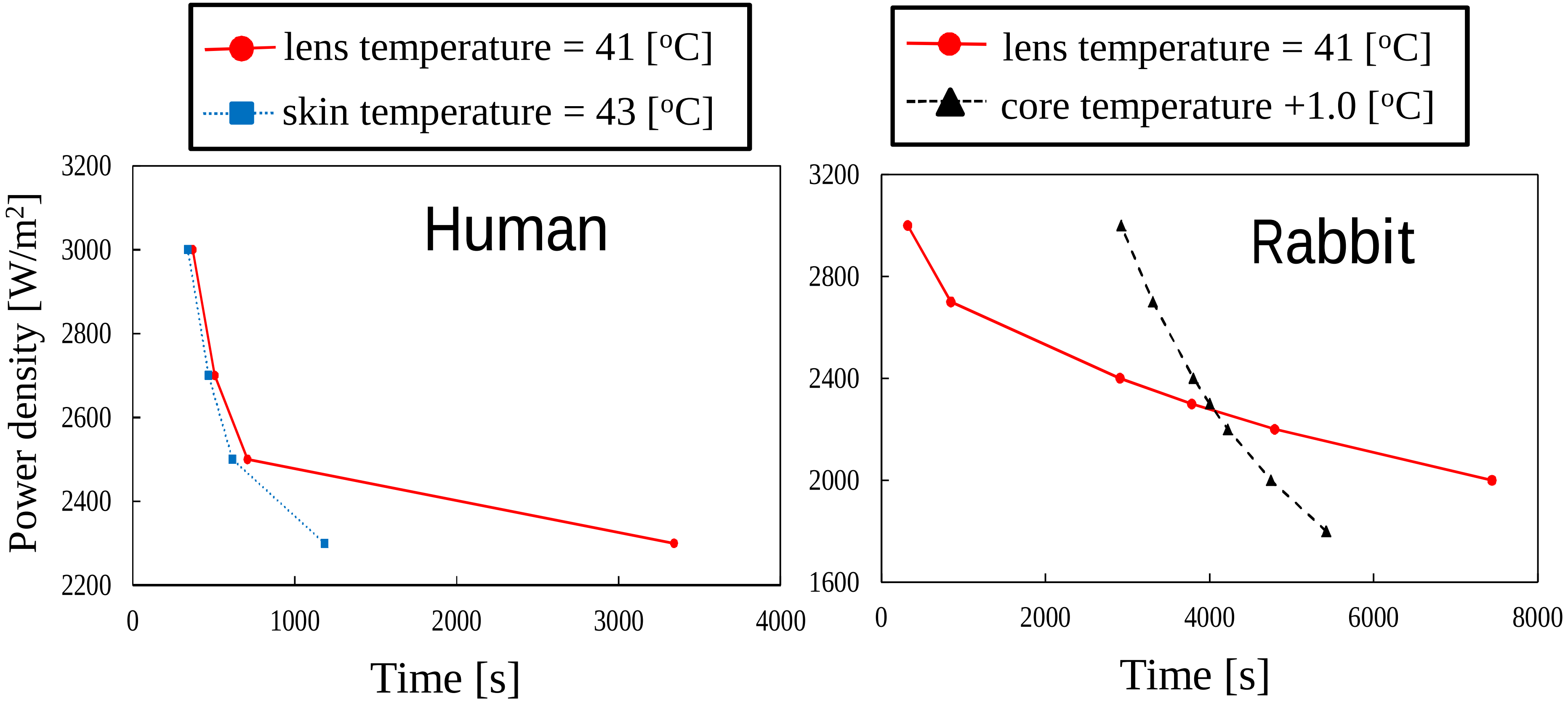
Temperature Variation in Human and Rabbit

- Frequency: 2.45GHz
- Incident power density: 3,000W/m^2



T. Oizumi et al , Radiation Prot. Dosimetry, 2013

Exposure Duration required for threshold temperatures in Human



- **The facial burning observed in monkeys (Kramer, 1978) was expected even for a human model.**

Thank you!