HF Dosimetry

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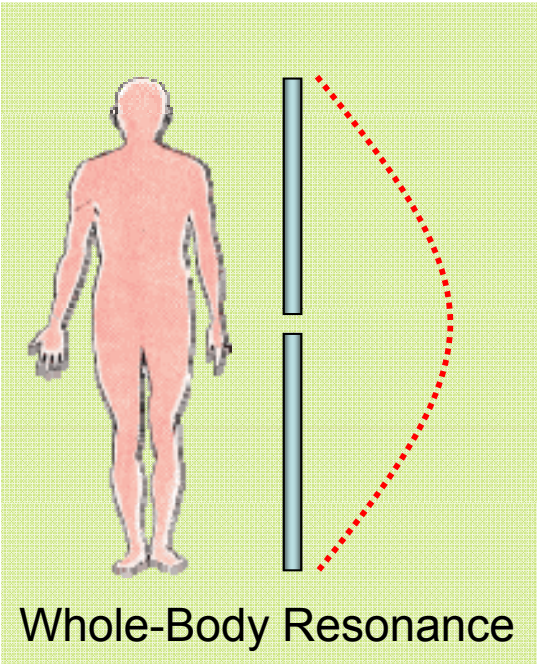
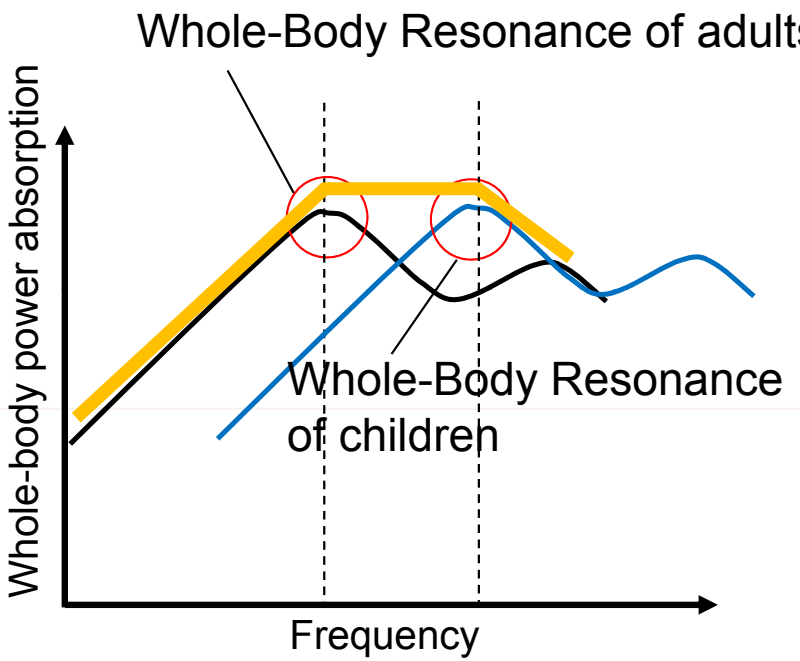
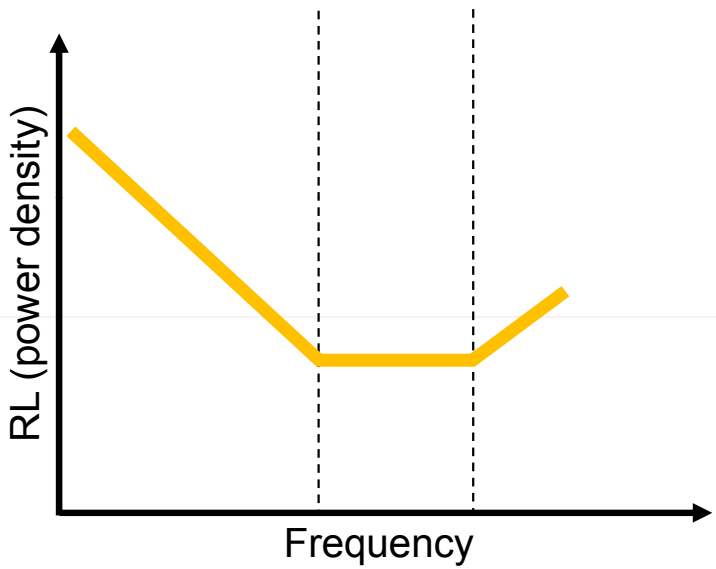
Dosimetry in HF region

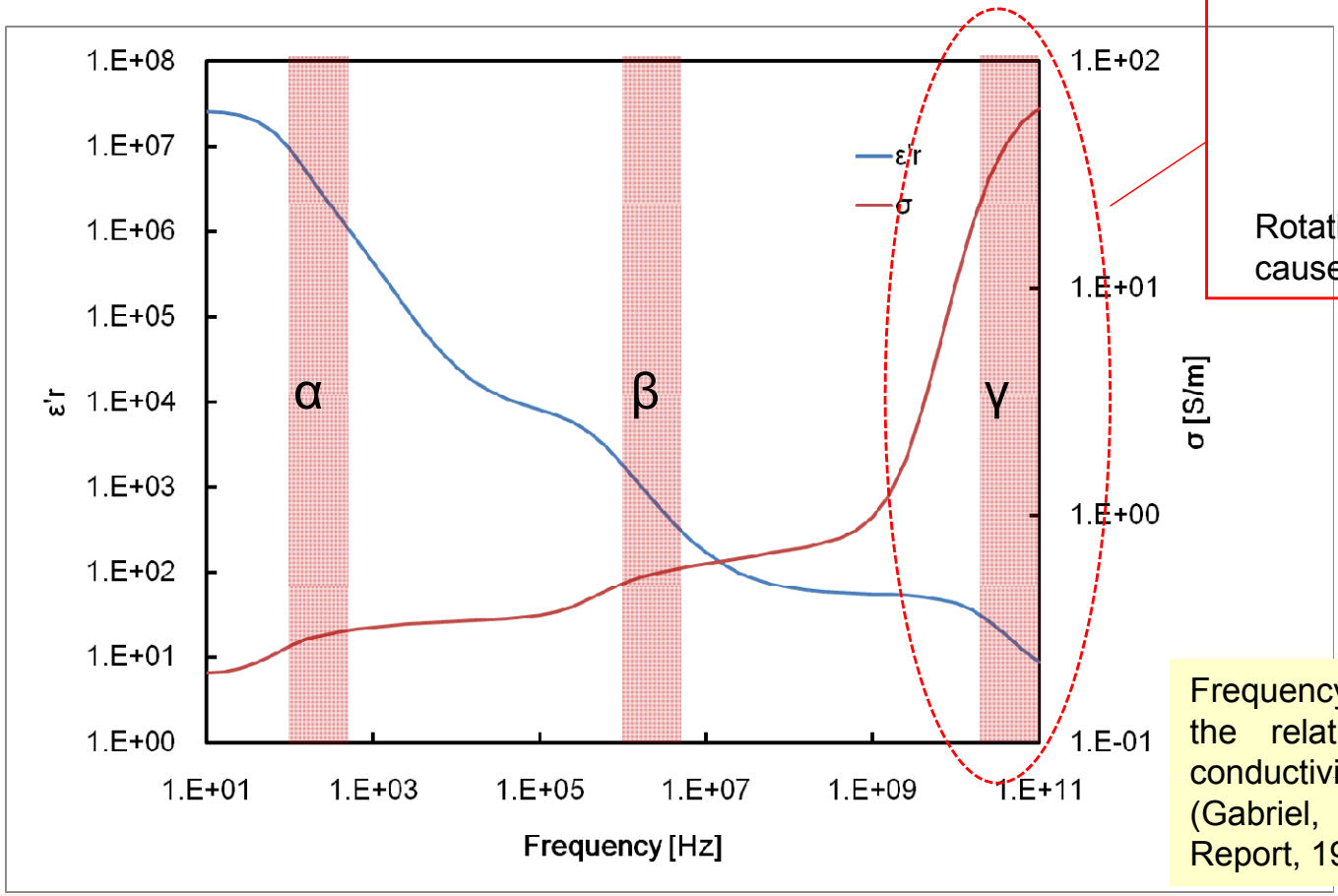
- Dosimetry has acted the important function in deriving the HF guidelines;
  - Relationship between the temperature elevation and the BR, or SAR and power density.
  - Relationship between the BR and the RL, or electric, magnetic and power density. The most known outcome of the HF dosimetry is the RL considering the whole-body resonance phenomenon.

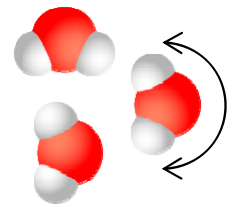






Electrical properties of biological tissues and organs





Rotation of water molecules† causes γ dispersion.

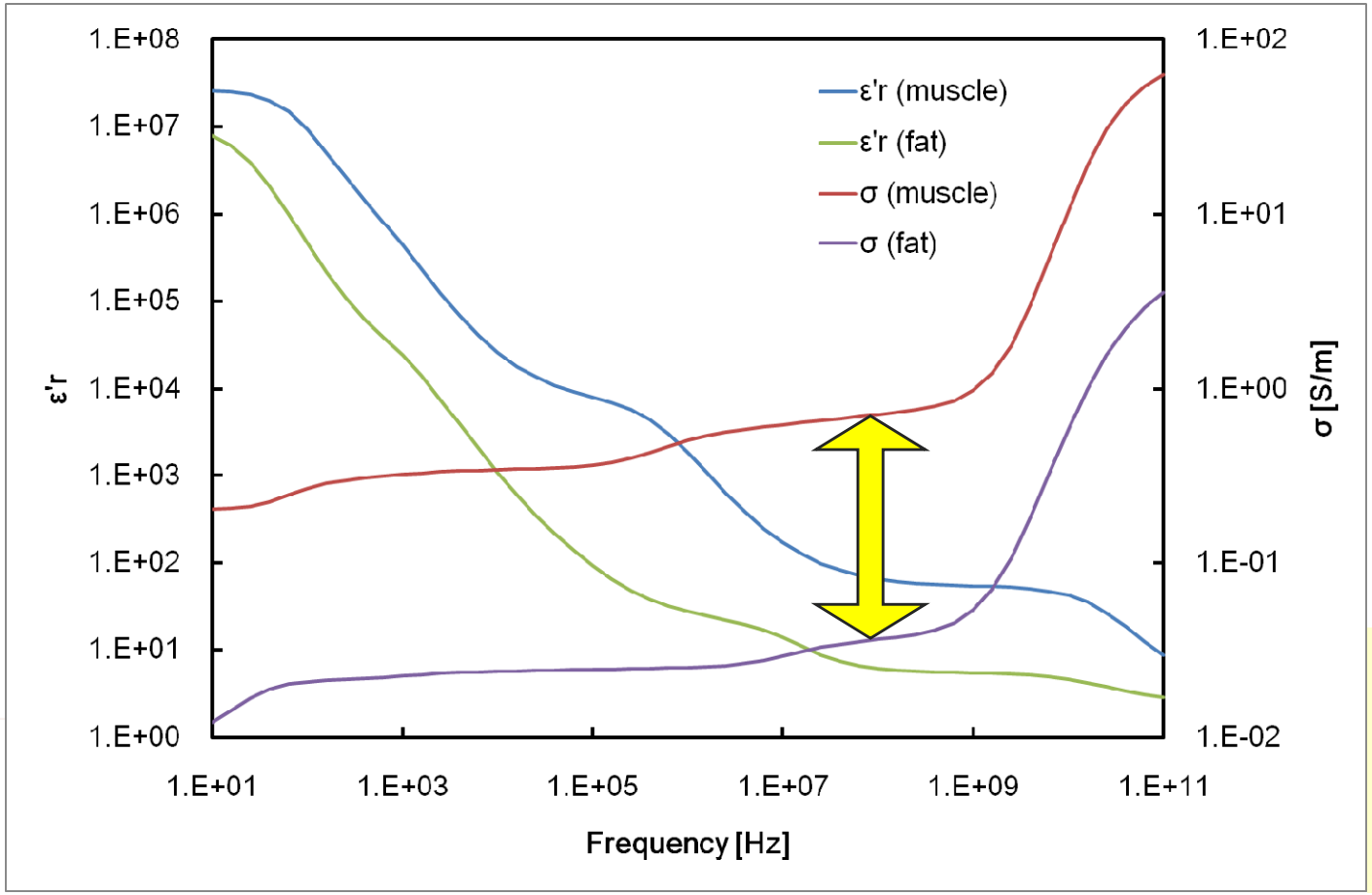
Frequency characteristics of the relative permittivity and conductivity of muscle tissue (Gabriel, et al., Brooks AFB Report, 1996).

Three relaxations, known as **α, β, and γ dispersion**, appear in the frequency characteristics of the electrical properties of the biological tissues or organs.

(†) http://commons.wikimedia.org/wiki/File:Water_molecule.svg

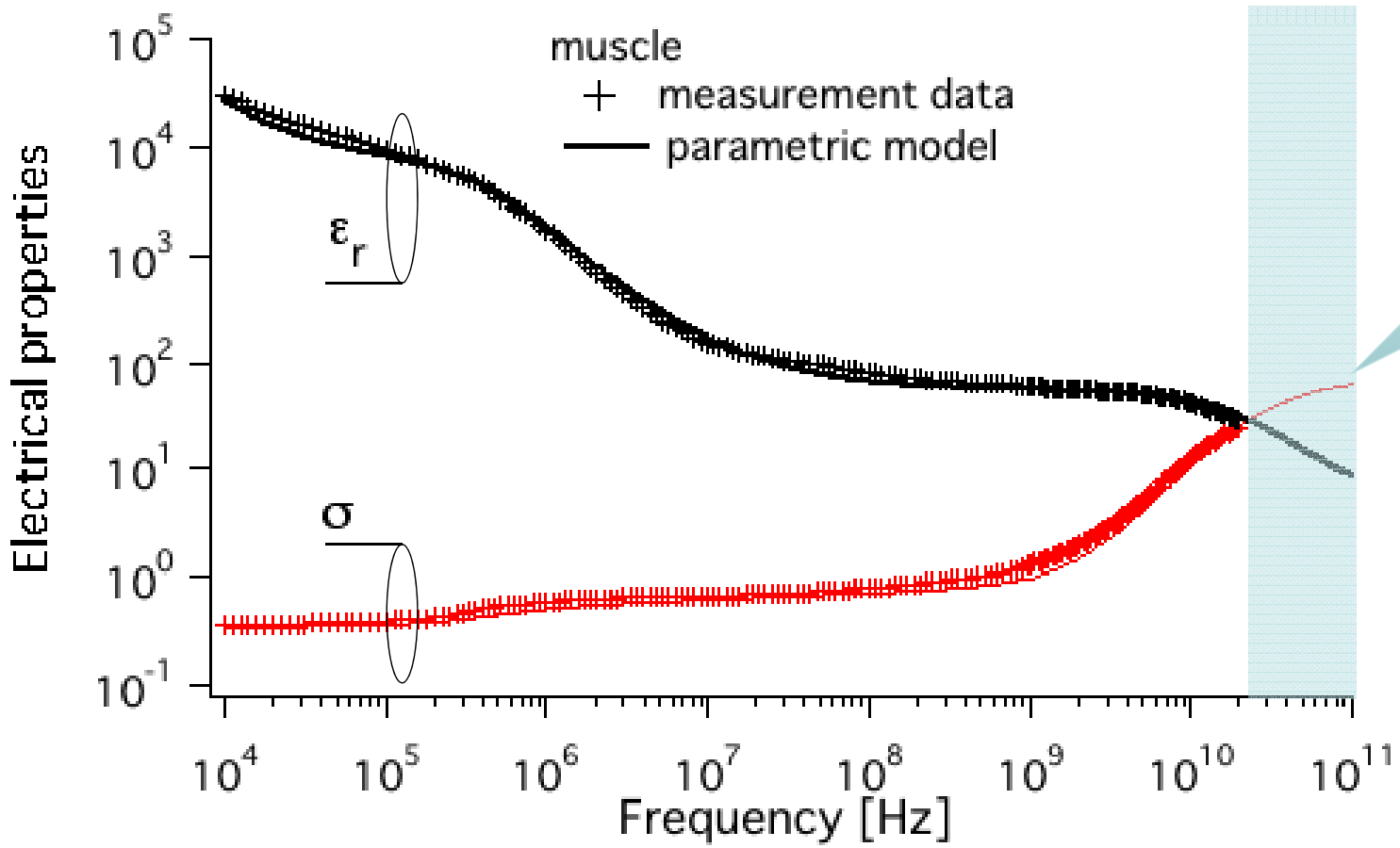
Variability of electrical properties

Electrical properties of biological tissues and organs are significantly variable, which can be 100 times or more and depends on the **water-content ratio**.



Frequency characteristics of the relative permittivity and conductivity of muscle as a high-water-content tissue and fat as a low-water-content one (Gabriel, et al., Brooks AFB Report, 1996).

1996 Gabriel's database



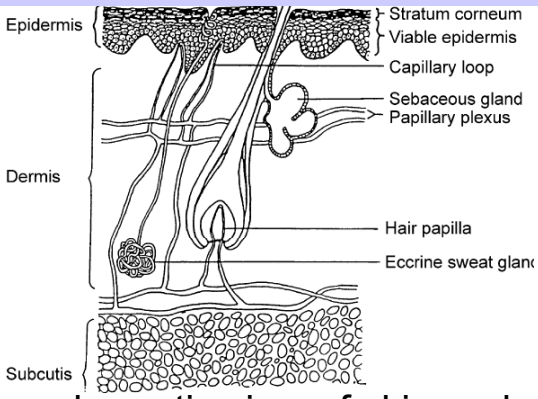
typically extrapolated from the measurement data below 20 GHz

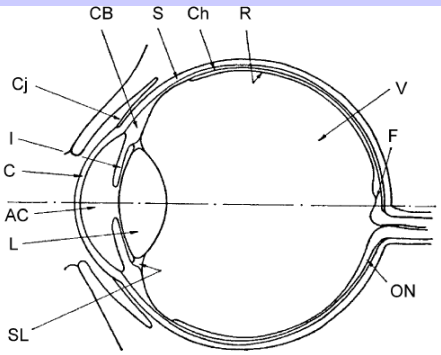
resent research gave the data of the tissues over surface of the body. (skin and eye tissues)

electrical properties of muscle
(Gabriel, et al., Brooks AFB Report, 1996)

Recent update on the electrical properties in HF region (1/2)

- Skin tissues; from 0.5 GHz to 3 THz
  - epidermis (*in vivo*, human); 0.1 THz-3 THz
  - stratum corneum and the rest of the epidermis plus dermis (*in vivo*, human); 37 GHz-74 GHz
  - epidermis and dermis (*in vitro*, pig); 0.5 GHz-110 GHz
- Eye tissues; from 0.5 GHz to 100 GHz
  - cornea, iris, lens, sclera, and vitreous (*in vitro*, rabbit)
  - aqueous humour (*in vitro*, pig)





schematic view of skin and eye tissues (ICRP, 2002)

Physics in Medicine and Biology

In vivo study of human skin using pulsed terahertz radiation

E Pickwell[1,2], B E Cole[2], A J Fitzgerald[2], M Pepper[1,2] and V P Wallace[2]

Published 1 April 2004 • 2004 IOP Publishing Ltd

Physics in Medicine and Biology, Volume 49, Number 9

Skin Research and Technology 2008; 14: 390–396
Printed in Singapore · All rights reserved
doi: 10.1111/j.1600-0846.2008.00319.x

Millimeter wave reflectivity used for measurement of skin hydration with different moisturizers

S. I. Alekseev, I. Szabo and M. C. Ziskin

Center for Biomedical Physics, Temple Univ

Bioelectromagnetics 28:331–339 (2007)

Human Skin Permittivity Determined by Millimeter Wave Reflection Measurements

S.I. Alekseev[1,2] and M.C. Ziskin[1]*

Publishing | Institute of Physics and Engineering in Medicine — Physics in Medicine and Biology

Phys. Med. Biol. 59 (2014) 4739–4747 — doi:10.1088/0031-9155/59/16/4739

Measurement of the dielectric properties of the epidermis and dermis at frequencies from 0.5 GHz to 110 GHz

K Sasaki, K Wake and S Watanabe

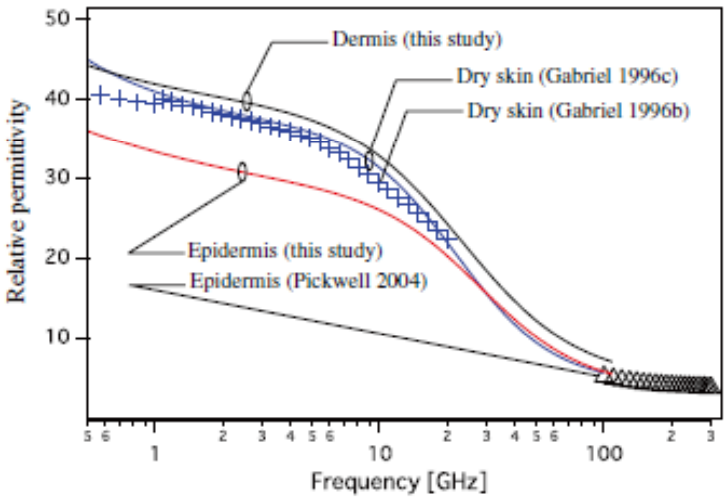
IOP Publishing | Institute of Physics and Engineering in Medicine — Physics in Medicine & Biology

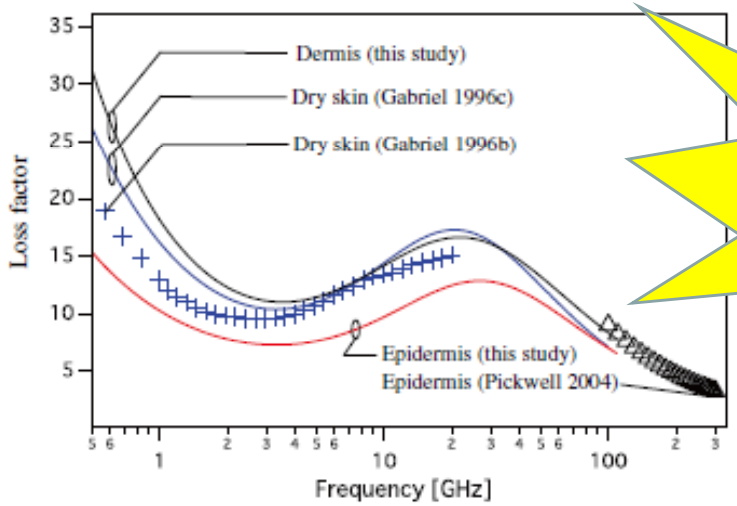
Phys. Med. Biol. 60 (2015) 6273–6288 — doi:10.1088/0031-9155/60/16/6273

Dielectric property measurement of ocular tissues up to 110 GHz using 1 mm coaxial sensor

K Sasaki[1], Y Isimura[1,2], K Fujii[1], K Wake[1], S Watanabe[1], M Kojima[3], R Suga[2] and O Hashimoto[2]

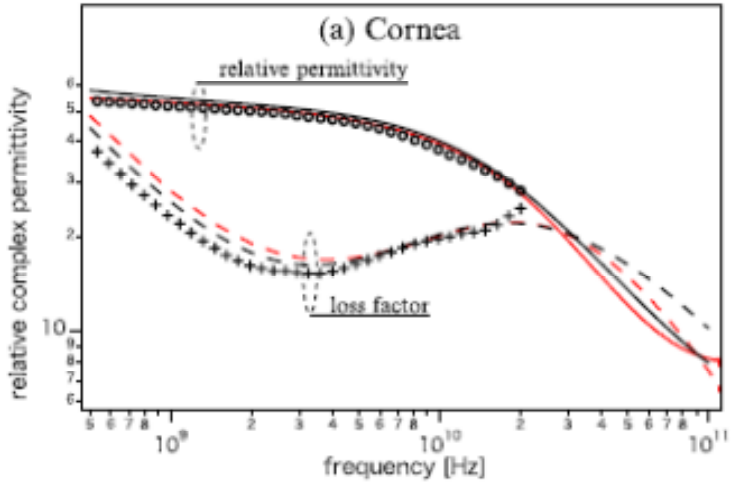
Recent update on the electrical properties in HF region (2/2)

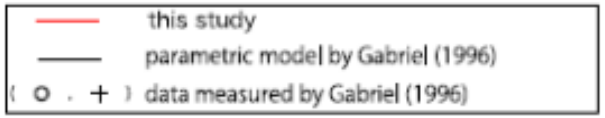




Large discrepancy appears in skin tissues.

Sasaki et al., PMB, 2014



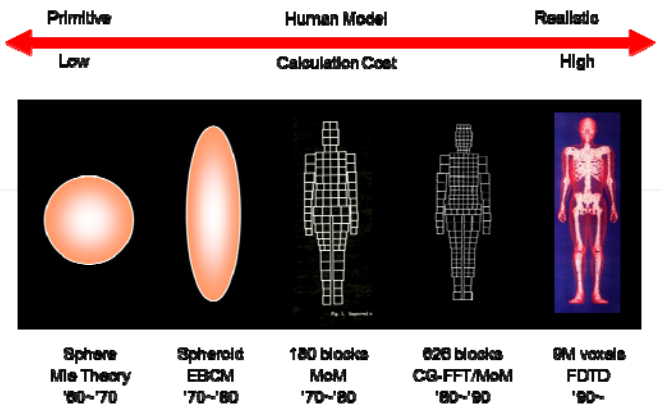


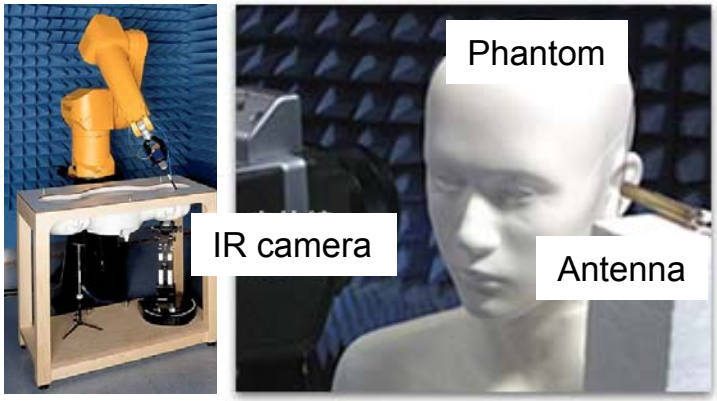
Sasaki et al., PMB, 2015

Human modeling in HF region

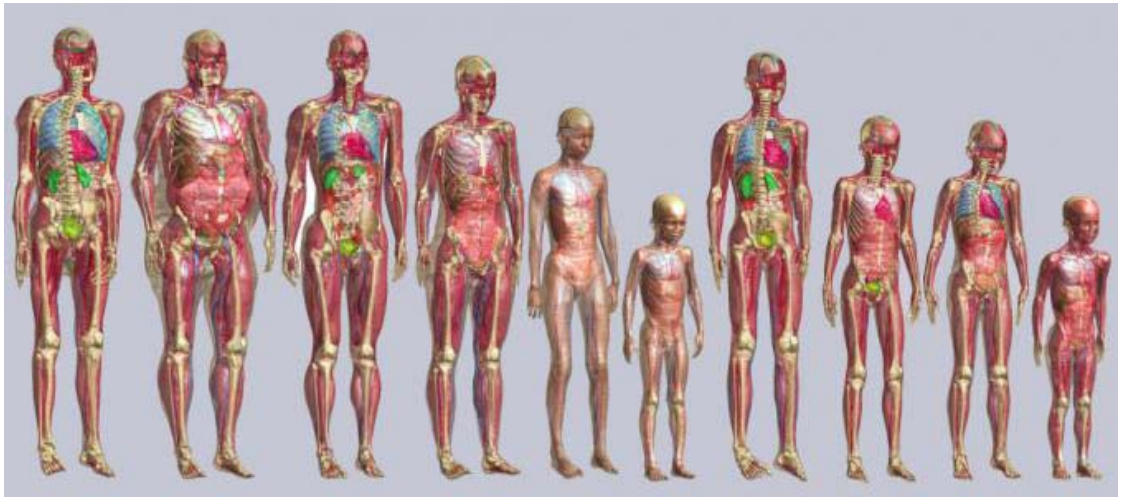
In the dosimetry, a surrogate of a human body has been used. For theoretical studies, analytical or numerical human models have been used. For experimental ones, physical human phantoms have been used.

- **Numerical human models are one of the most important advances in the dosimetry, which have fine spatial resolutions with accurate anatomical structure based on CT and MRI technology.**
- Physical human phantoms have relatively poor anatomical structure, frequently consist of single material such as tissue-equivalent liquid. However the physical human phantoms have widely been used in the compliance evaluations of radio devices because actual radio devices can be used for the evaluation and the simple phantom can provide highly-reproducible and worst-side evaluation.

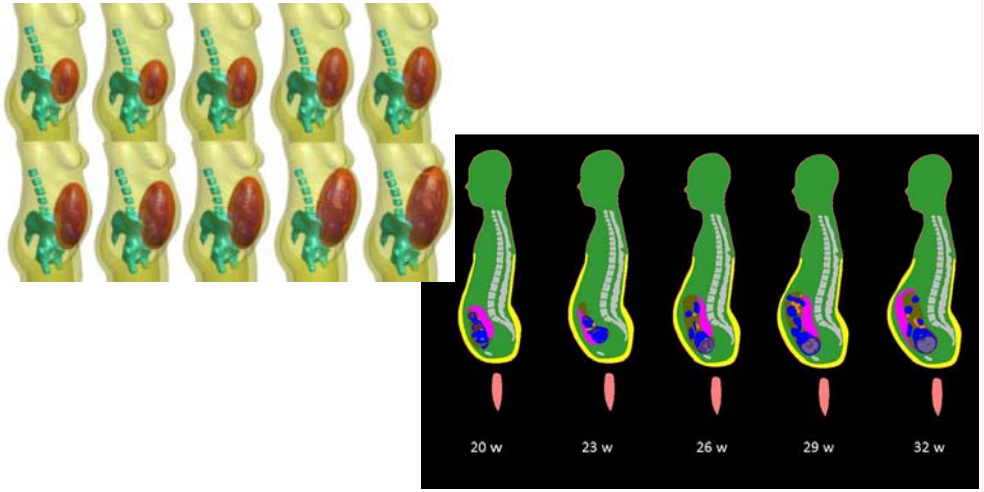




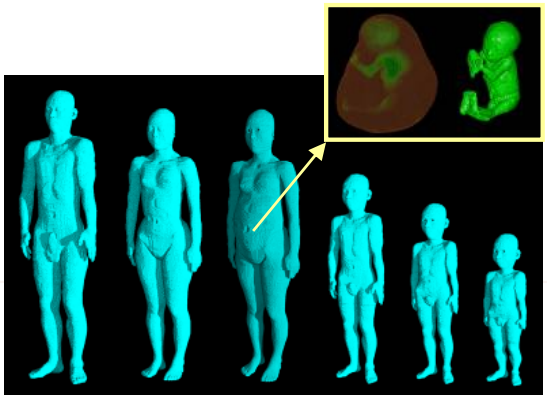
Latest numerical human models

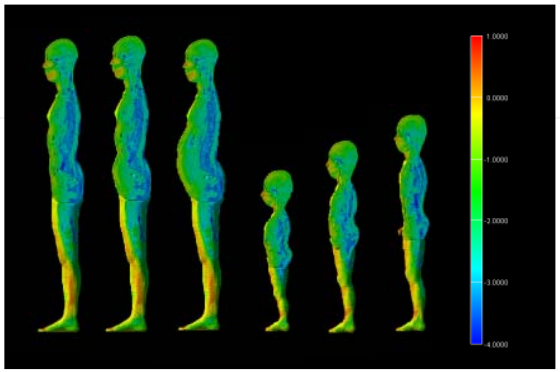


From the homepage of IT'IS foundation.

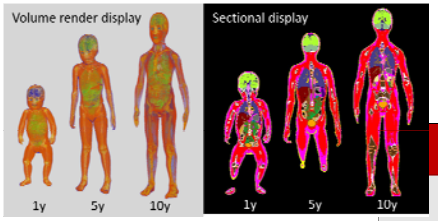


France-Japan research project (FETUS)





NICT's voxel human models.



	Developed models		ICRP ref. data		% Diff. from ICRP ref. data	
	Height (cm)	Weight (kg)	Height (cm)	Weight (kg)	Height	Weight
1y	76.0	9.4	76.0	10.0	0.0	6.21
5y	109.0	18.8	109.0	19.0	0.0	0.92
10y	138.0	32.2	138.0	32.0	0.0	0.69

New child models with ICRP specifications.
Details are shown in a poster by Nagaoka et al.

Uncertainty in HF dosimetry

Uncertainty, defined by ISO/IEC Guide 98, is usually evaluated with its expanded value which covers **95% confidential interval** of the probability distribution of the evaluated result. Uncertainty of EMF dosimetry depends on many factors. **30% or 1 dB** may be a reasonable target for a specific case with a technique of state of the art in HF region while larger uncertainty has been recognized in LF region, i.e., 3-dB reduction factor due to the uncertainty of the dosimetry is considered in deriving RLs in LF region.

Uncertainty of HF numerical dosimetry and other factors considered in the reduction factor

Uncertainty of numerical techniques;
- Approximation of Maxwell's eq.,
- Boundary conditions,
- Convergence,
- Post processing (local averaging).

Uncertainty of discrete modeling;
- Approximation with staircase of smooth shape,
- Spatial resolution vs complex heterogeneous structure.

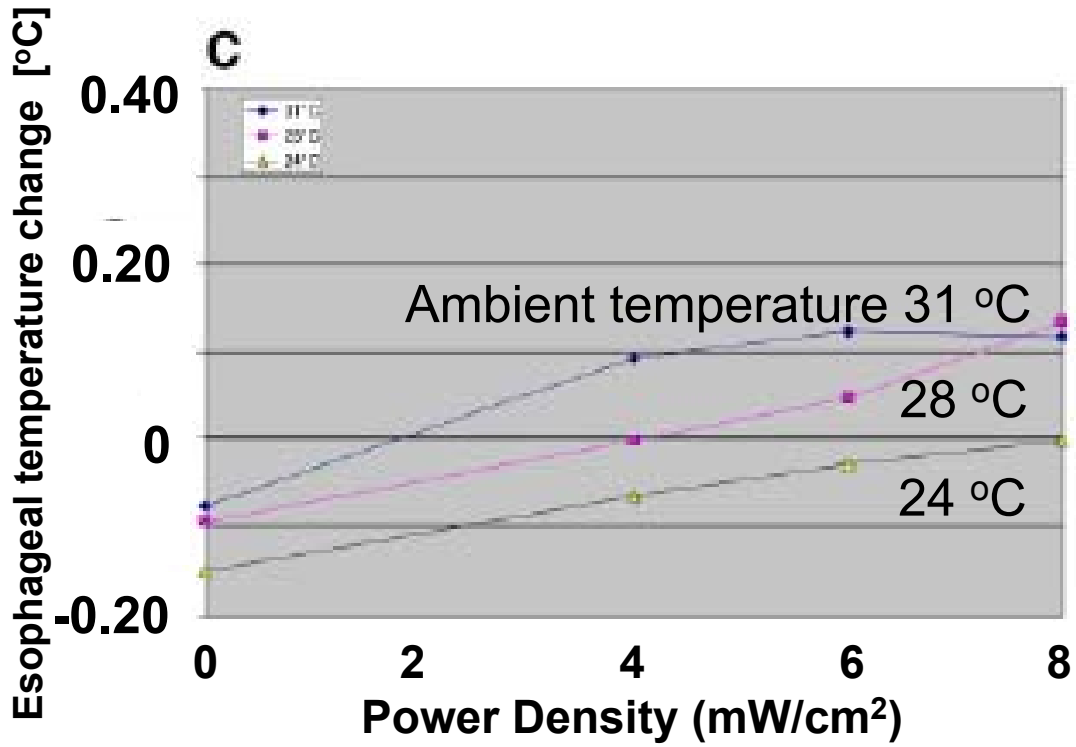
Variation of a human body, population;
- Size and weight,
- Internal structure (fat thickness).

Variation of exposure conditions;
- Polarization and direction,
- Reflection and grounding,
- Other source conditions.

Other factors to be considered.

Reduction factor

Thermal Dosimetry for whole-body exposure: back exposed at 100 MHz

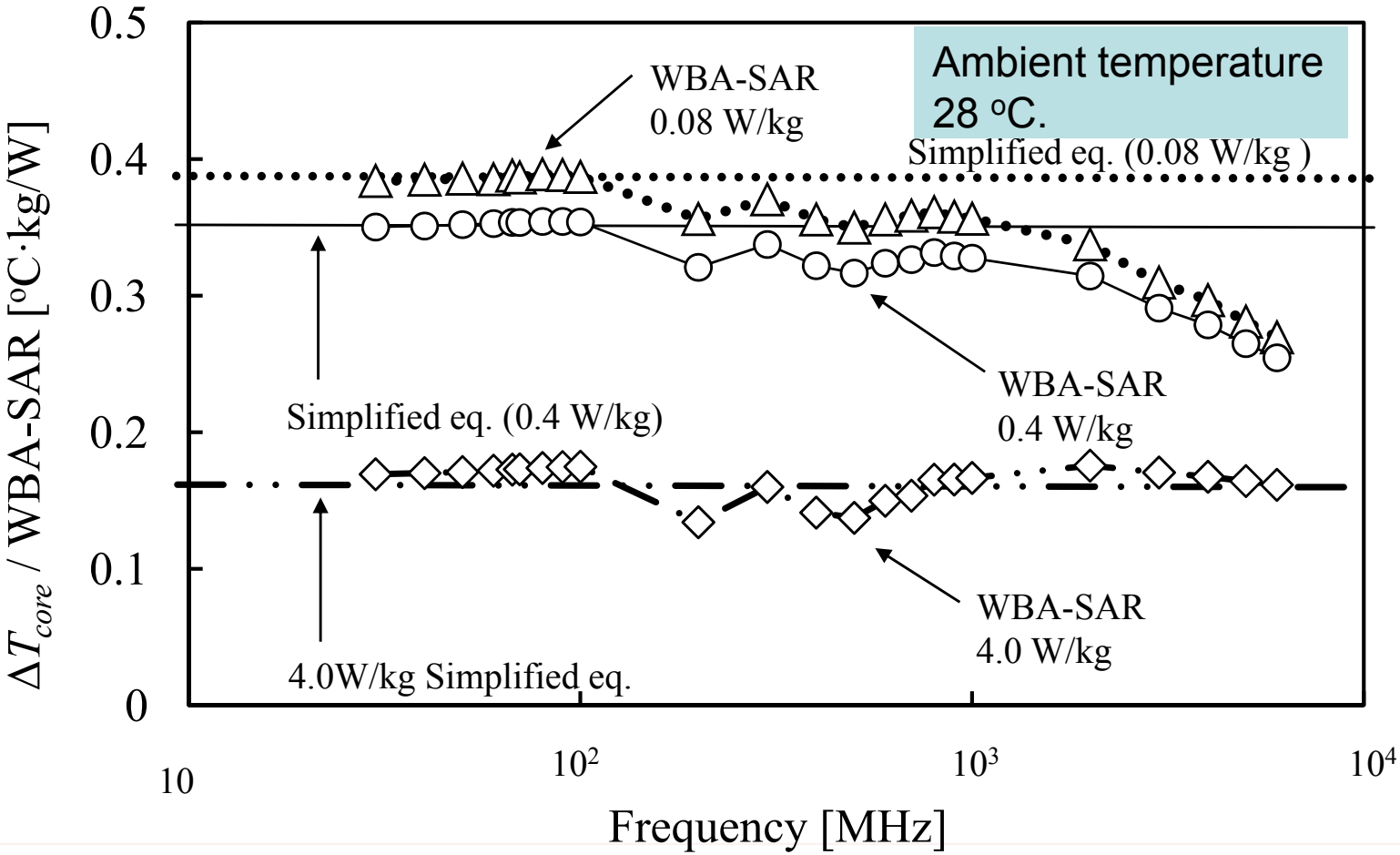


Exposure duration
45 min

Whole-body average (WBA) SAR at 0.68 W/kg for duration of 45 min.
Measured ΔT = 0.15-0.20 °C (100 MHz) Adair
Computed ΔT = 0.177 °C@28 °C (65 MHz) unpublished
Computed ΔT = 0.17 °C@28 °C (100 MHz) by Nelson

Adair et al, Bioelectromagnetics, 2003
Hirata et al, Phys. Med. Biol., 2007.
Laakso & Hirata, Phys. Med. Biol., 2011.
Nelson et al, Phys. Med. Biol., 2014

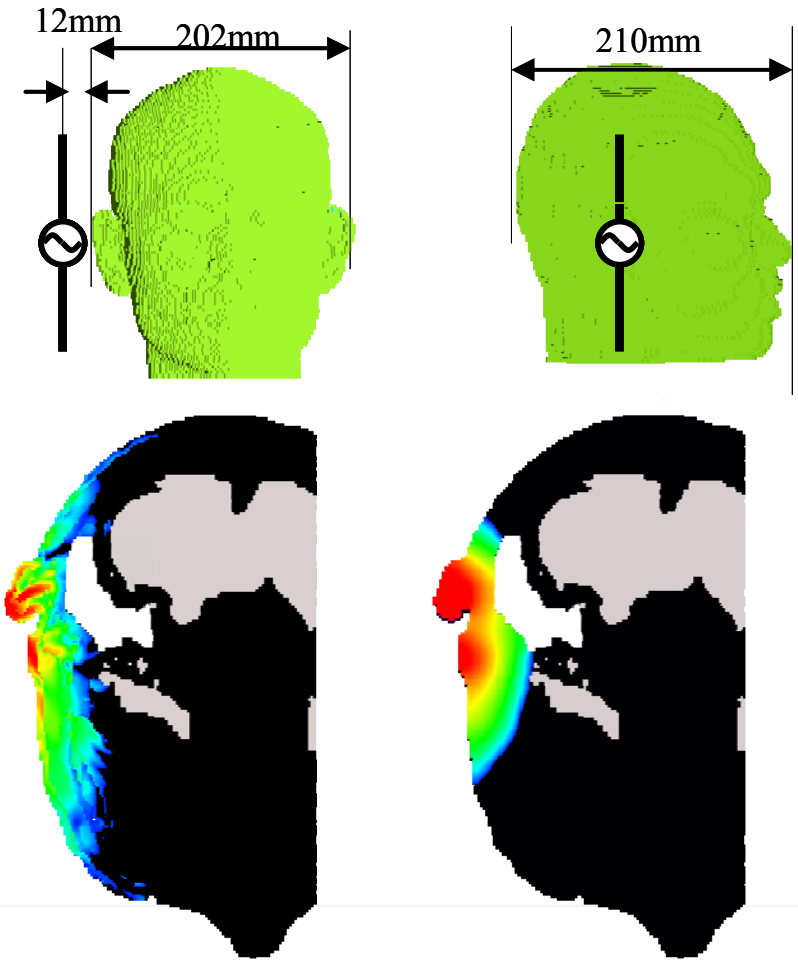
Core temperature elevation normalized by WBA-SAR



In the elderly, thermoregulatory response is weaker than that in the young adult due to declined heat sensitivity etc, resulting in higher core temperature.

Hirata et al, Phys. Med. Biol., 2013

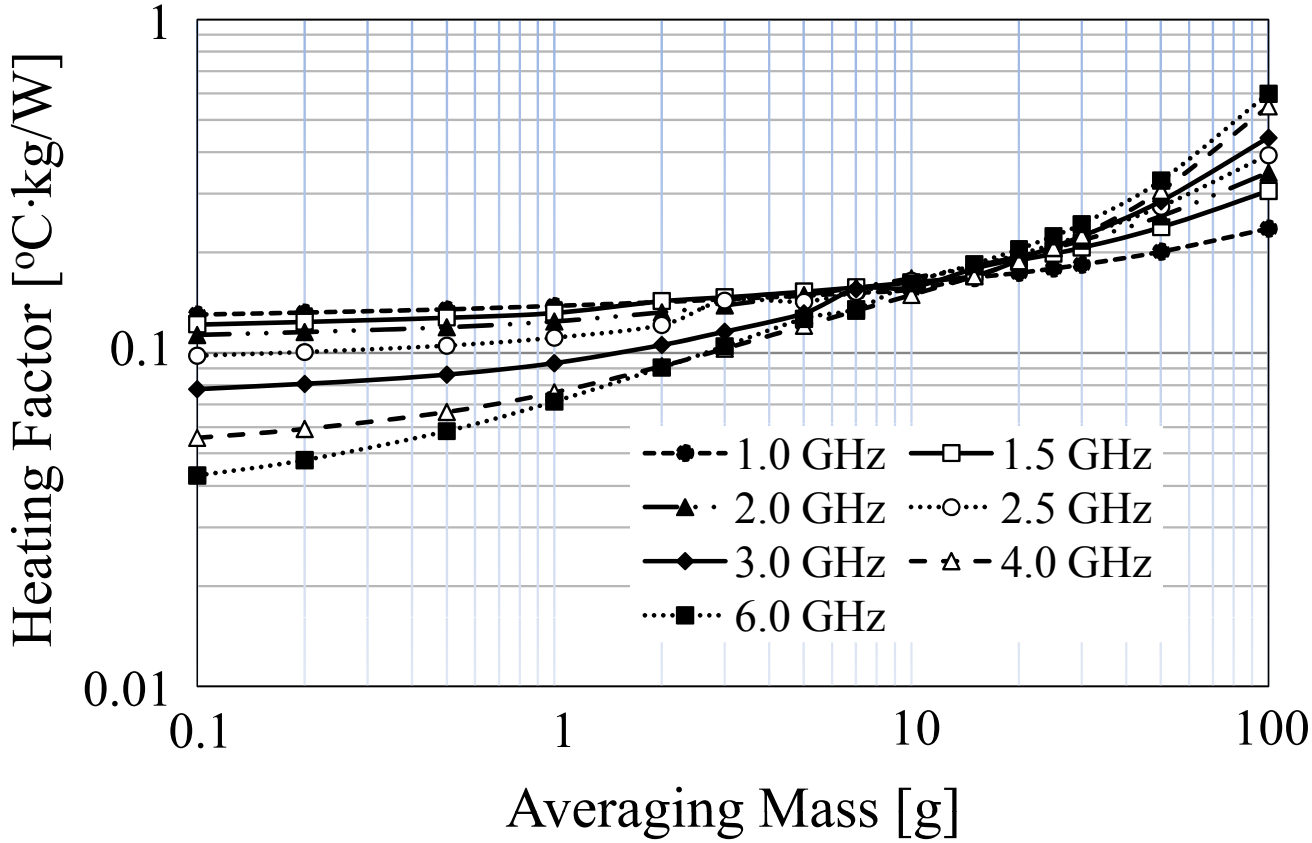
Local temperature elevation in anatomical head models



- Frequency=6 GHz
- Thermal steady state (~30 min); depending on the frequency
- Temperature elevation distribution in the human model is smoother than that of SAR due to heat diffusion.

◆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)
◆McIntosh et al. (BEMS, 2010)

Effect of averaging mass: Averaged SAR vs Temperature Elevation



The heating factors converge at the averaging mass of ~10 g.
ΔT can be estimated in terms of SAR at different frequencies.

Hirata et al, Phys. Med. Biol., 2009

The blood flow may increase for the temperature elevation caused by local exposure.
The heating factors without considering the response are conservative.

Alekseev et al, BEMS, 2005

Maximum local temperature elevation by local SAR (10 g)

Tissue	Heating Factor $^{o}CW^{-1}kg$	Frequency GHz	Averaging	Exposure data	Reference
Brain	0.13 0.18 0.22 [1)] 0.21 0.12	1 2.5 5 0.9-2.45 0.915	cube, 10 g cube, 10 g cube, 10 g	Plane wave,upfront, female adult Near field averages, adult, Near field	Laakso 2009 Fujimoto et al. 2006 Van Leeuwen 1999
Eye	0.1 -0.12 (lens) 0.13 (lens) 0.11-0.147 (lens) 0.22 (lens) 0.16-0.17 (lens) 0.18-0.19 0.21 0.23	1-3 7.5 0.6-3 5 0.9-1.9 0.380-1.8 1 3	cube, 10 g eye 7.5 g Eye 11.5 g eye, 9.4 g cube, 10 g	Plane wave averages, male, Plane wave, adult Near fields and plane wave Near field Plane wave and near fields	Laakso 2009 Hirata et al. 2007 Hirata 2005 Wainwright 2007 McIntosh et al. 2010
Skin, fat, pinna, muscle	0.2-0.26 0.28-0.37	1-3 6	cube,10 g	Plane wave and near fields	McIntosh et al. 2010

Temperature elevation for millimeter wave exposure

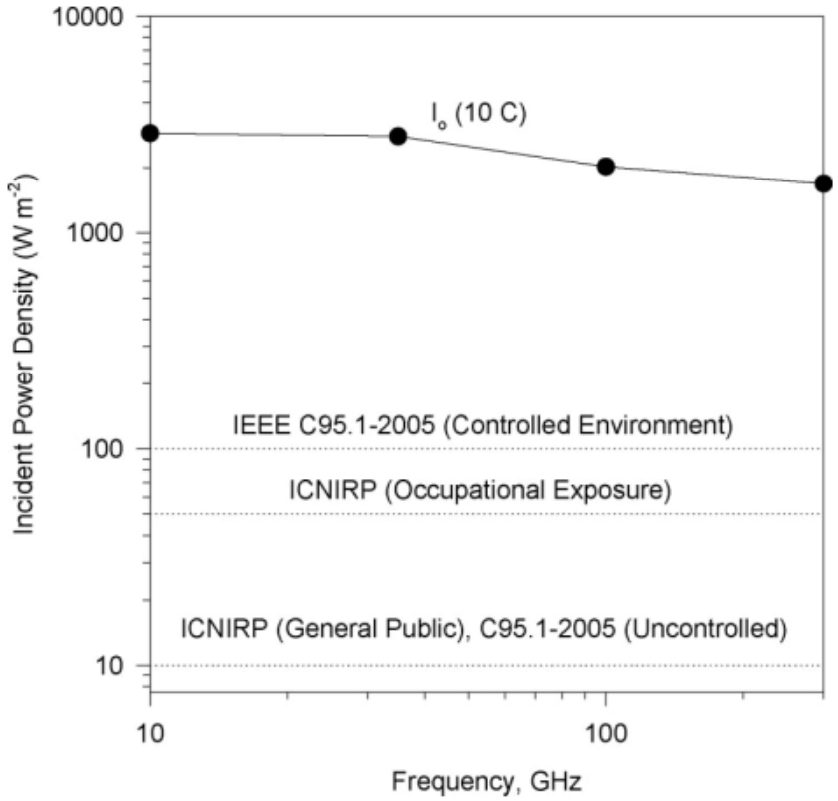


Fig. 1. Incident power density sufficient to increase skin temperature by 10°C, considered to be the threshold for thermal pain. Also shown are IEEE C95.1-2005 and ICNIRP exposure limits.

Foster et al, Health Phys., 2010

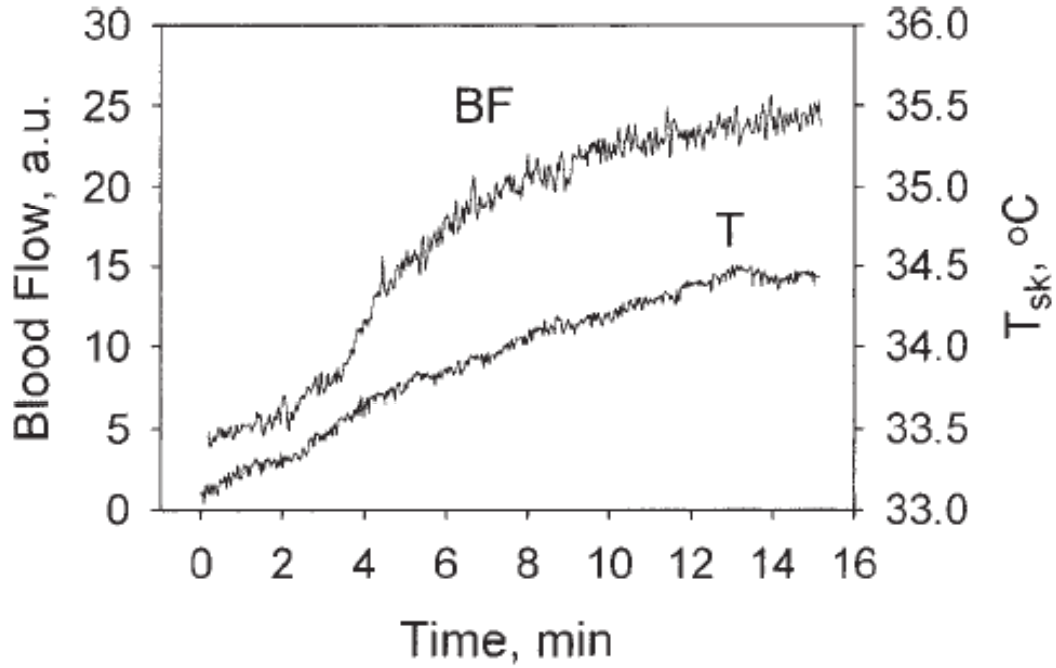
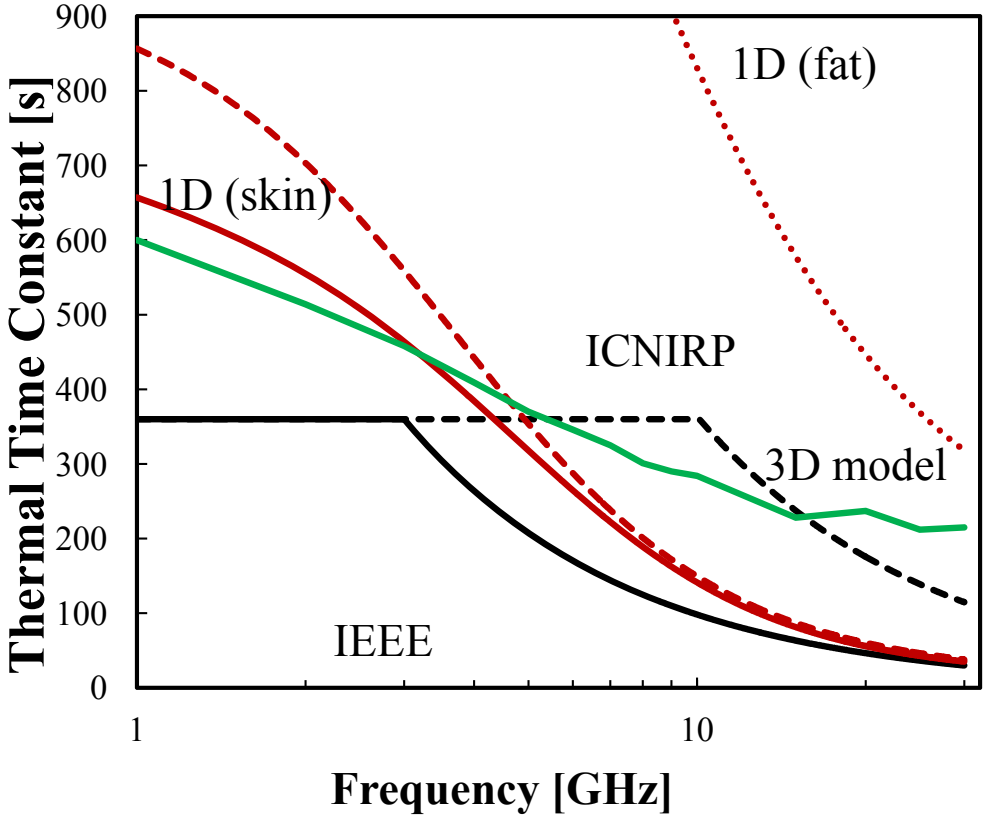
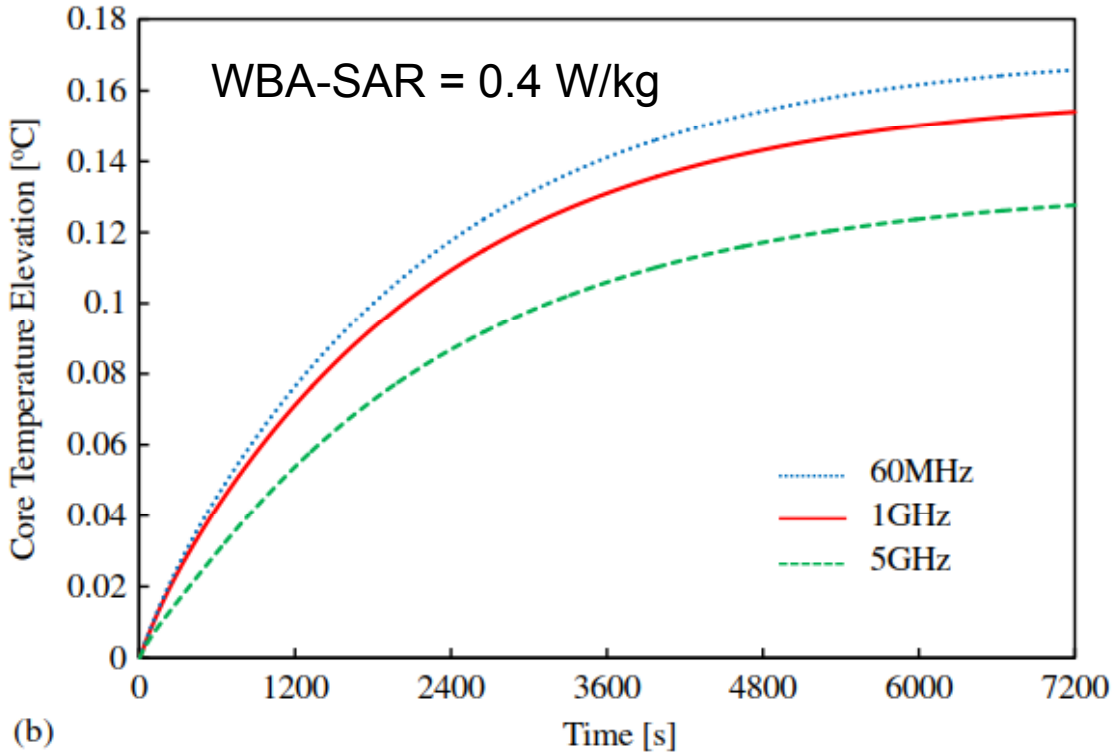


Fig. 7. Blood flow (BF) and temperature (T) changes in the forearm skin following a vasodilator cream (nicoboxil/nonivamid) application.

Alekseev et al, Bioelectromagnet., 2005

Thermal Time Constants for Local and Whole-body Exposures

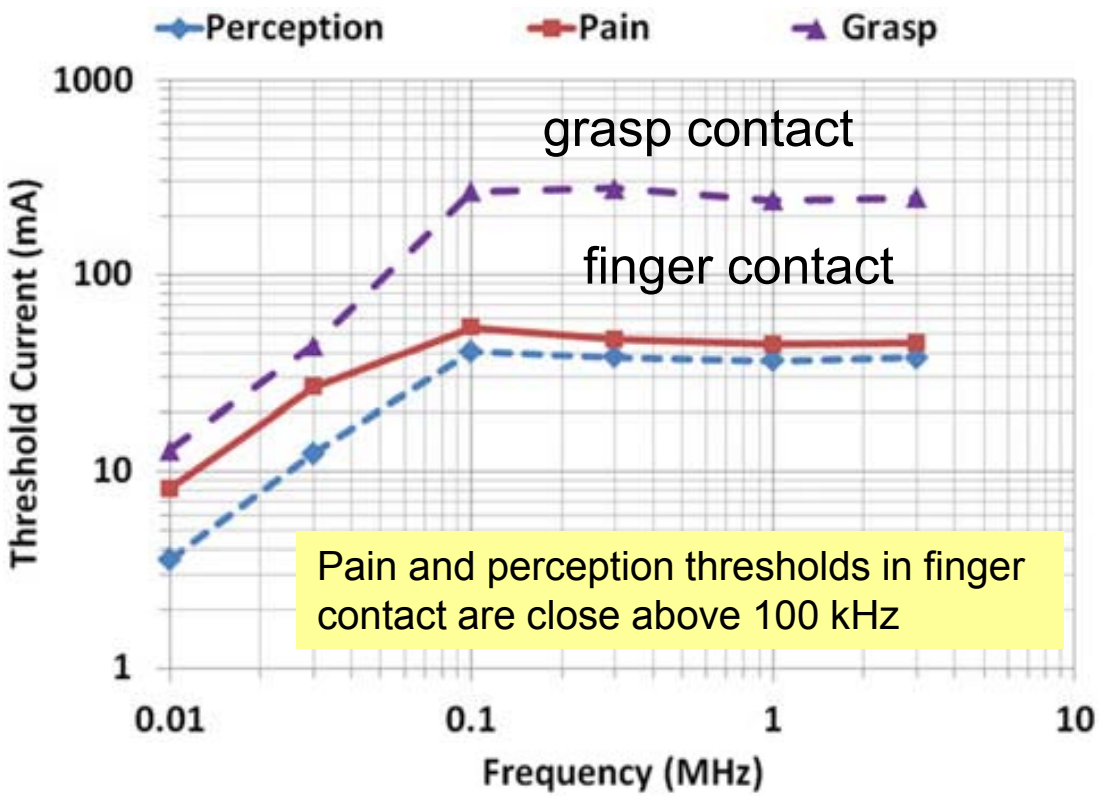




Foster et al, Bioelectromagnetics, 1998

Hirata et al, Phys. Med. Biol., 2013

Threshold of perception and pain due to contact current



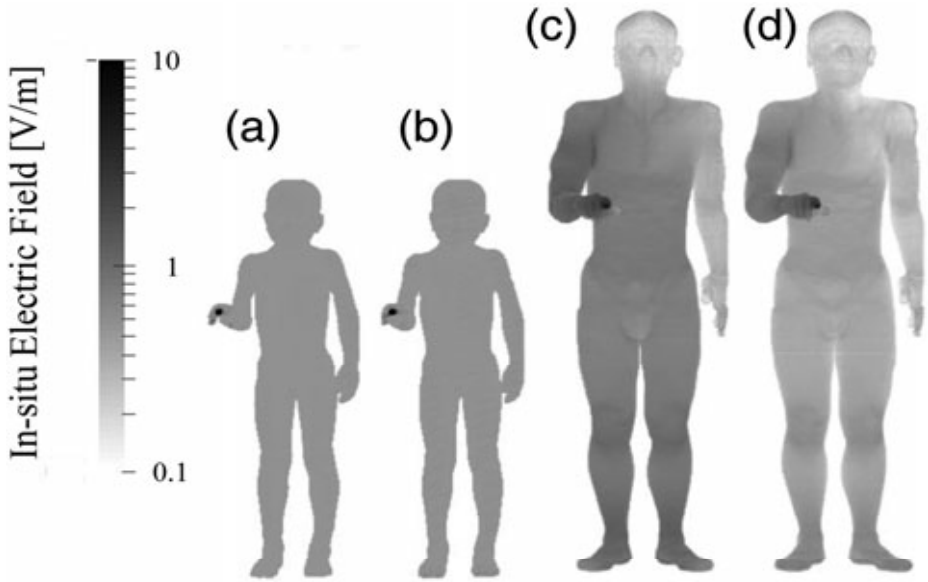
Chatterjee et al. 1986

- Above 100 kHz, heat sensation. Below 100 kHz, sensation of electrostimulation.
- Pain threshold in finger may reach the heat perception threshold after 10-20 s.
- Pain is due to the stimulation of nociceptors in the cutaneous and subcutaneous tissues.
- Skin temperature elevation from 34 to 36 ^{o}C at rate of 4°C/s elicits a pain sensation (Green et al.2010).

Local SAR induced by contact current of 40 mA in finger of an adult

Frequency (MHz)	SAR_{10g} (W/kg) [1]
0.1	468
1	393
10	469
100	387

[1] IEEE averaging scheme



Extremely high SAR in finger

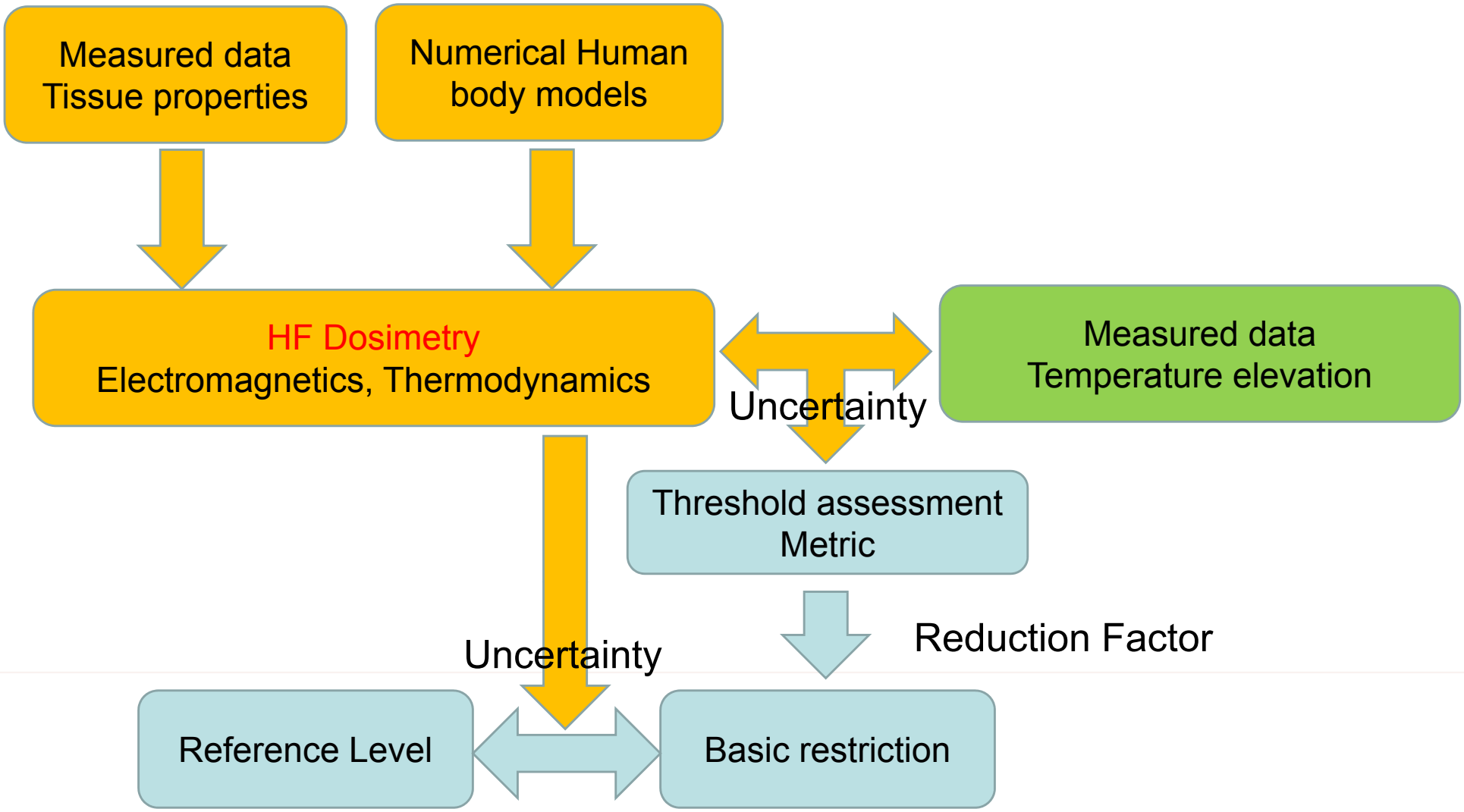
40 mA=ICNIRP1998 reference level for occupational exposure

20 W/kg=ICNIRP 1998 basic restriction for occupational exposure

SAR scaled from 16 mA to 40 mA (Table 8)

Chan et al., Phys. Med. Biol., 2013

Summary


Measured data
Tissue properties
Numerical Human body models
HF Dosimetry
Electromagnetics, Thermodynamics
Uncertainty
Measured data
Temperature elevation
Threshold assessment
Metric
Reduction Factor
Uncertainty
Reference Level
Basic restriction

ICNIRP Guidelines above 300 GHz (Laser)

Table 5. Laser exposure limits for the eye, expressed as irradiance or radiant exposure at the cornea; for the retinal limits, also expressed as power or energy, where the exposure is to be determined as power or energy through a 7 mm aperture.[a,b]

Wavelength (nm)	Exposure duration: Lower limit	Exposure duration: Upper limit	Exposure limit ($W\ m^{-2}$ or $J\ m^{-2}$)	Exposure limit (W or J)	Restrictions
$1\,400 \le \lambda < 1\,500$	1 ms	10 s	$5.6\ t^{0.25}\ kJ\ m^{-2}$		
$1\,500 \le \lambda < 1\,800$	1 ns	10 s	$10\ kJ\ m^{-2}$		
$1\,800 \le \lambda < 2\,600$	1 ns	1 ms	$1.0\ kJ\ m^{-2}$		
$1\,800 \le \lambda < 2\,600$	1 ms	10 s	$5.6\ t^{0.25}\ kJ\ m^{-2}$		
$2\,600 \le \lambda < 1$ mm	1 ns	100 ns	$100\ J\ m^{-2}$		
$2\,600 \le \lambda < 1$ mm	100 ns	10 s	$5.6\ t^{0.25}\ kJ\ m^{-2}$		
$1\,400 \le \lambda < 1$ mm	10 s	30 ks	$1.0\ kW\ m^{-2}$		

Table 7. Laser radiation exposure limits for the skin.[a]

Wavelength (nm)	Exposure duration: Lower limit	Exposure duration: Upper limit	Exposure limit	Restrictions
Ultraviolet				
$180 \leq \lambda < 400$	1 ns	30 ks	Same as EL for the eye See Table 5	3.5 mm limiting aperture[b]
Visible and short wavelength IRR				3.5 mm limiting aperture[b]
$400 \leq \lambda < 1{,}400$	1 ns	100 ns	$200\ C_A$ J m^{-2}	
$400 \leq \lambda < 1{,}400$	100 ns	10 s	$11\ C_A\ t^{0.25}$ kJ m^{-2}	
$400 \leq \lambda < 1{,}400$	10 s	30 ks	$2.0\ C_A$ kW m^{-2}	
Mid and long wavelength IRR[c]				
$1{,}400 \leq \lambda < 1$ mm	1 ns	30 ks	Same as EL for the eye See Table 5	3.5 mm limiting aperture[b]