EMF Dosimetry (ELF, IF, and MMW frequency regions)

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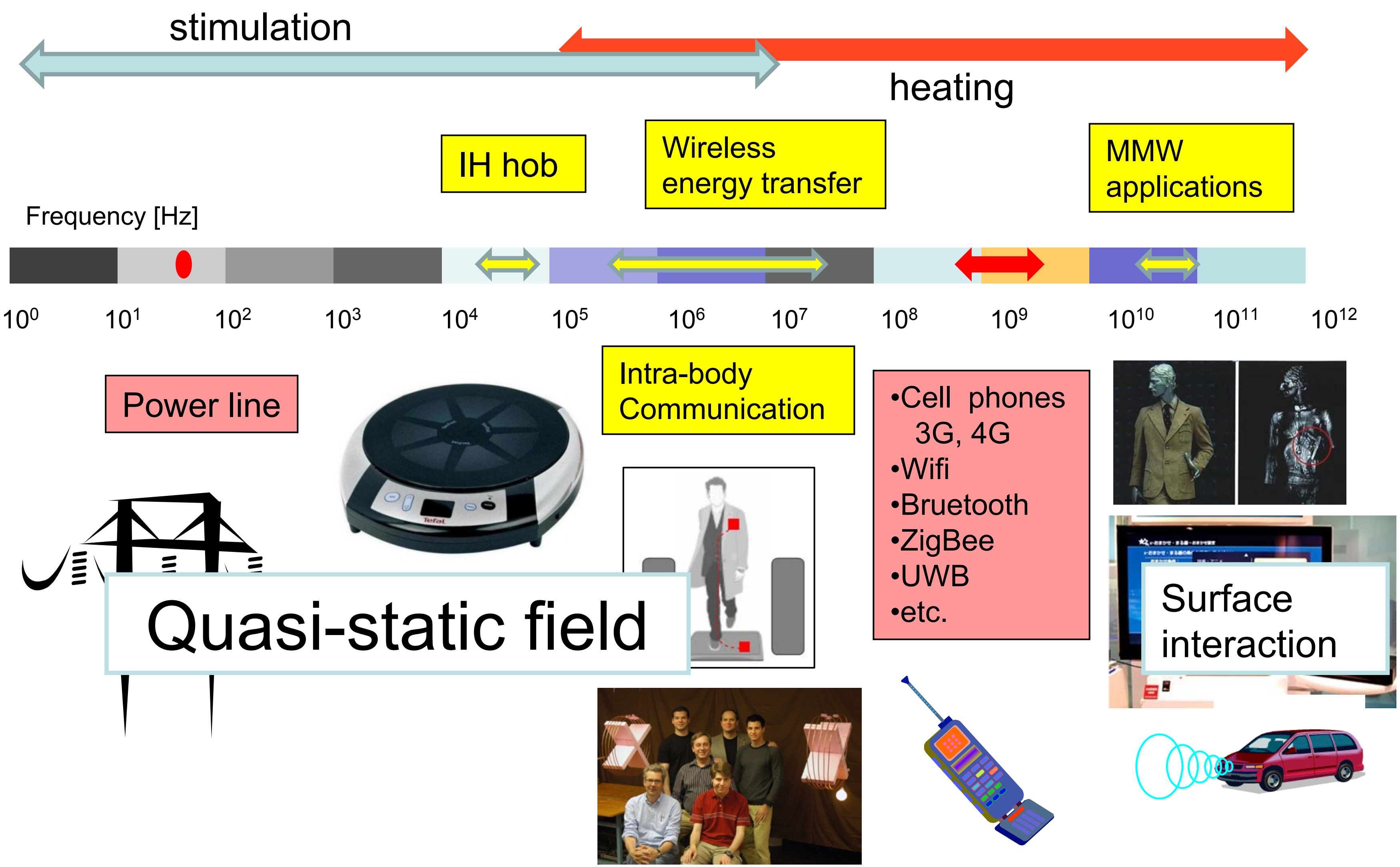
Technology in the Spectrum



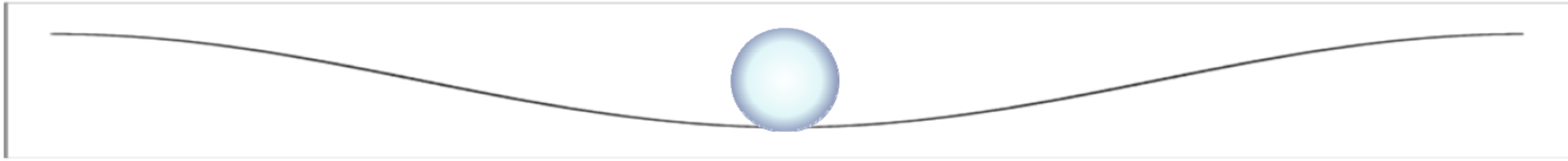
ELF AND IF DOSIMETRY

Role of ELF/IF dosimetry

- **Internal electric field** and **induced current density** are limited with the basic restrictions of ICNIRP guidelines in 2010 and 1998, respectively.
  - Assessment of compliance with basic restrictions is required for exposures from sources in the vicinity of human body
- **Reference levels** are recommended for the first-step assessment of exposure. Reference levels are given by measureable quantity such as electric and magnetic field strengths. In addition to them reference levels for **contact current** are recommended to avoid indirect coupling hazard.
  - Consistency of reference levels with basic restrictions need to be confirmed.

Method of ELF/IF dosimetry

Quasi-static field

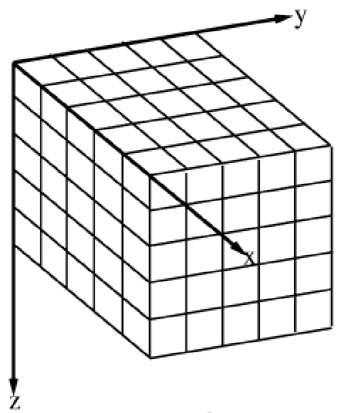


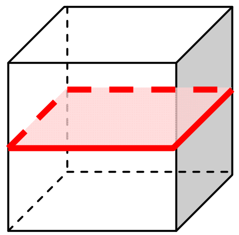
- When the wavelength is much smaller than the dimension of the exposed object, phase difference within the object is negligible .
- In this condition, secondary induction of electric field due to time derivative of magnetic field or that of magnetic field due to time derivative of electric field is negligible.
- The electric and magnetic field behaves as static field slowly varying with time.
- **This assumption can be applied in the frequencies below about 10 MHz when the exposed object is human body.**

Numerical methods for dosimetry of quasi-static field exposure

- Quasi-static approximation
  - Finite element method (FEM)
  - Impedance method
  - Scalar potential finite difference (SPFD) method
  - Quasi static FDTD method
- Full-wave approach (only for intermediate frequencies > 1MHz)
  - Finite-difference Time-domain (FDTD) method

Impedance Method (quasi-static)



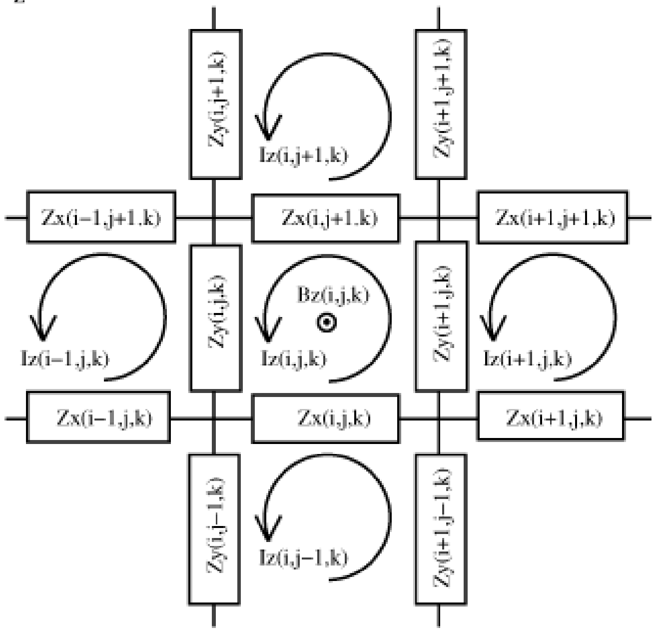


Impedance of the edge

$$Z(i,j,k) = \frac{1}{\sigma(i,j,k) + j\omega\varepsilon(i,j,k)} \times \frac{l}{S}$$

Electromotive force

$$V(i,j,k) = -\frac{d}{dt}\int \mathbf{B}\cdot\mathbf{n}\,\mathrm{d}S$$



A set of linear equations

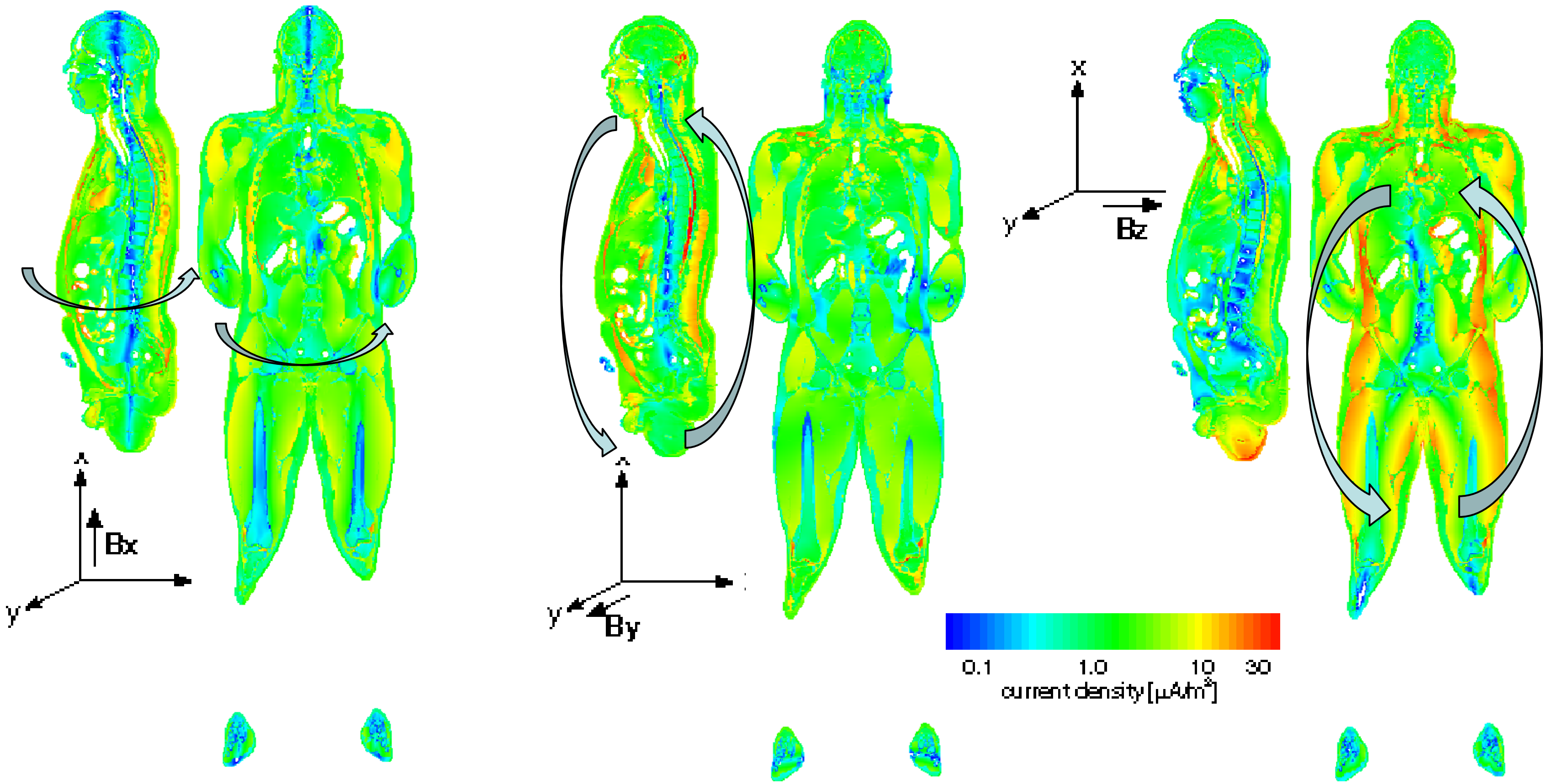
(loop equations derived from Kirchhoff's second law)

⇨ Successive Over Relaxation

Cf. SPFD method: Nodal equations derived from Kirchhoff's first law

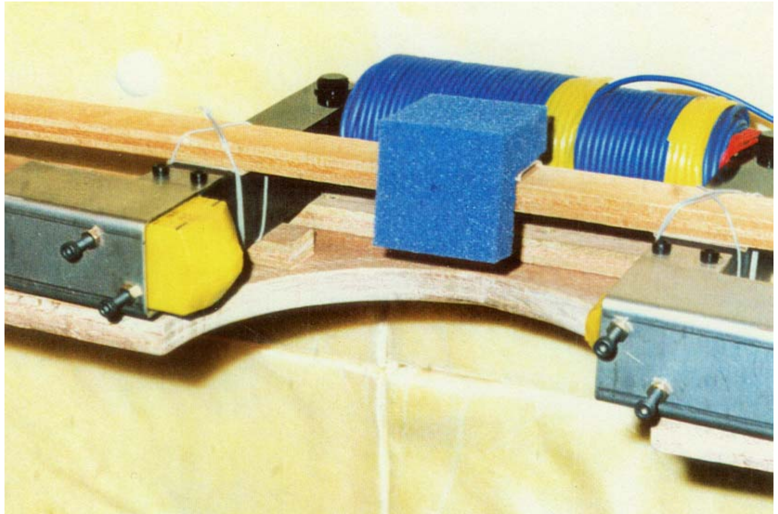
Examples of ELF dosimetry

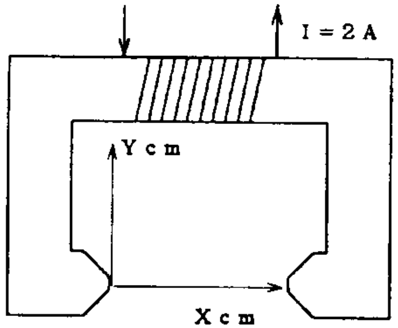
Induced current in human body by power frequency uniform magnetic field exposures

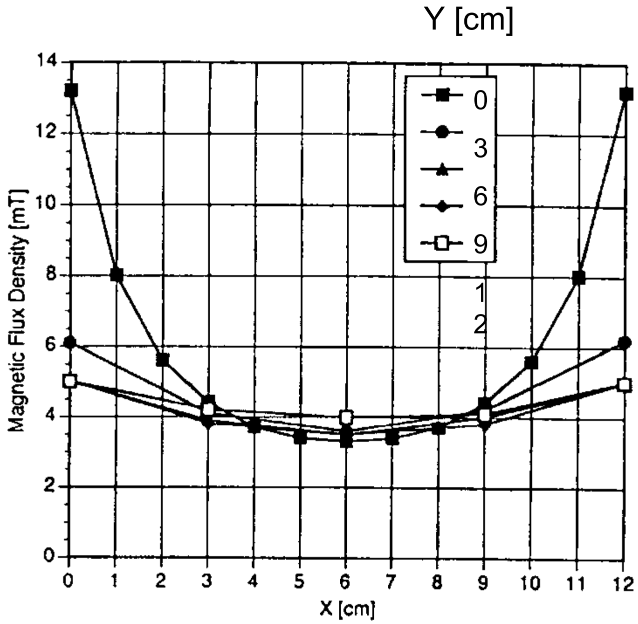


- Calculated with impedance method
- Homogeneous 1μT_{rms} magnetic fields of 50 Hz

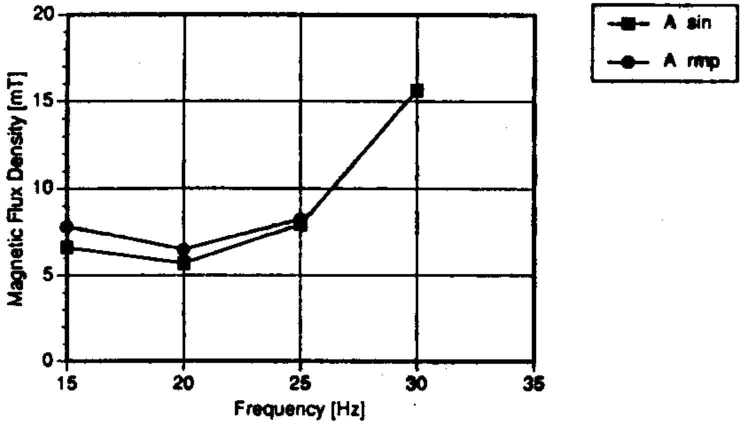
Magnetophosphene

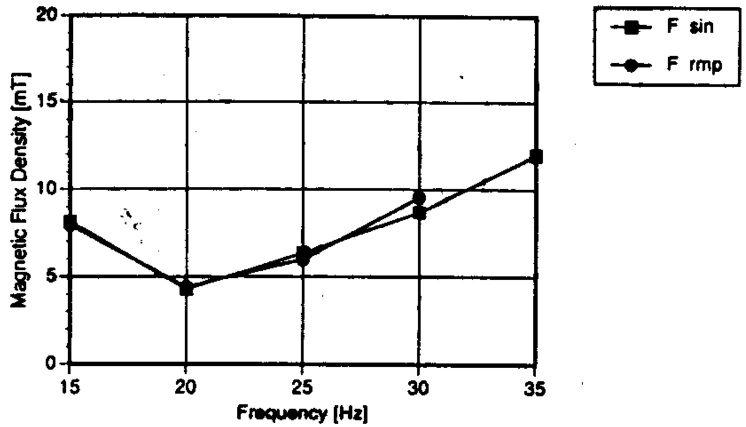


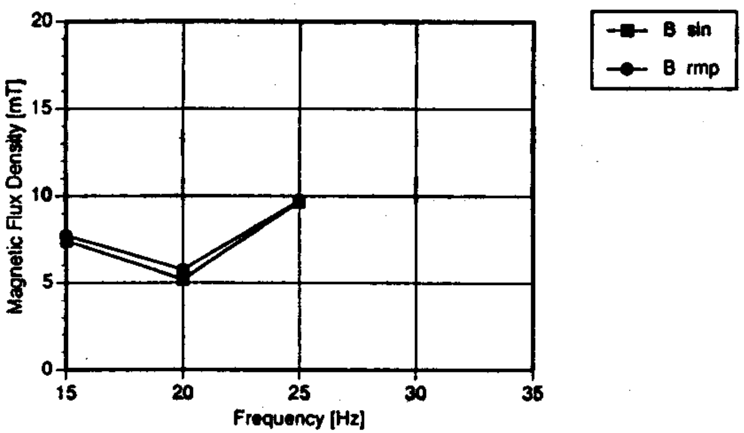


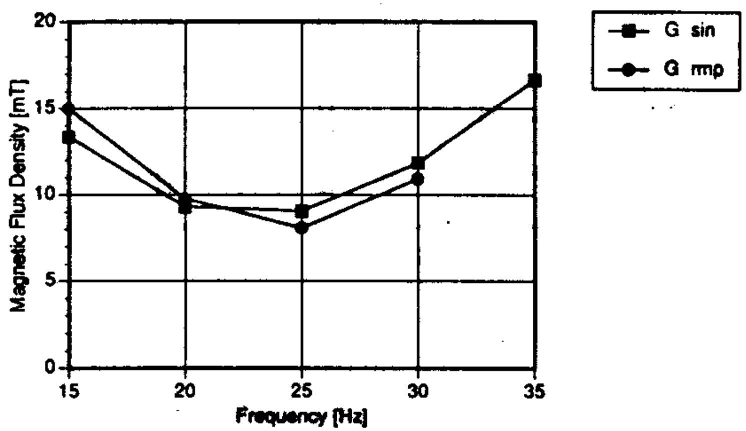


Measured Threshold of Magnetophosphene





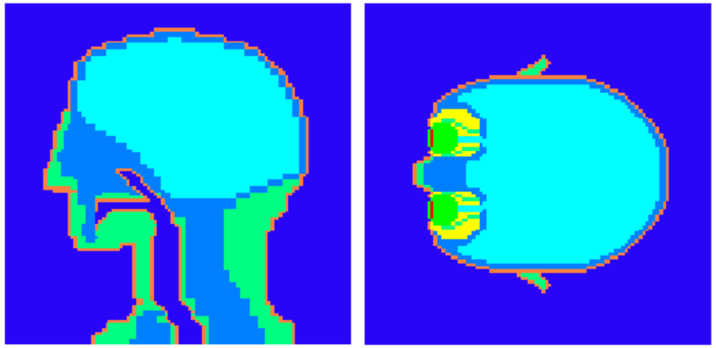




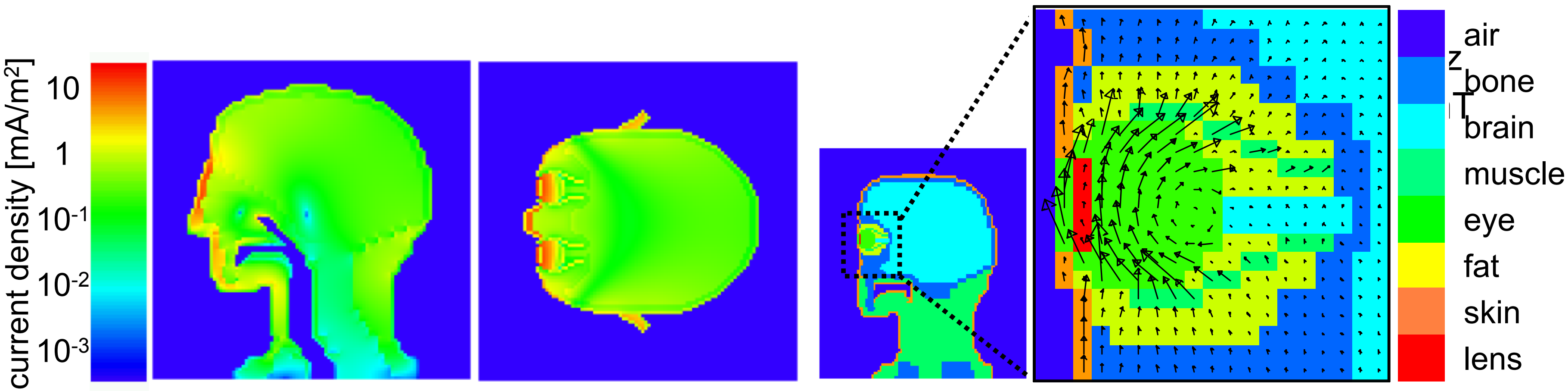
Head Model and induced current (impedance method)

- Heterogeneous human head

Resolution 2.5 mm



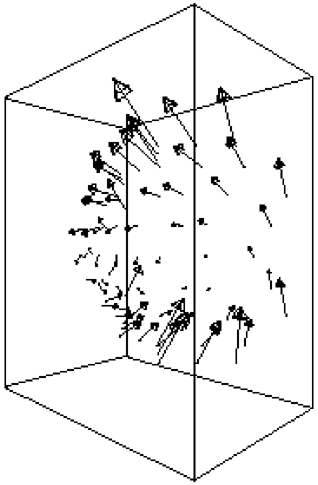
tissue	σ [S/m]
air	0
bone	0.07
brain	0.05
muscle	0.22
eye	1.5
fat	0.018
skin	0.1
lens	0.25

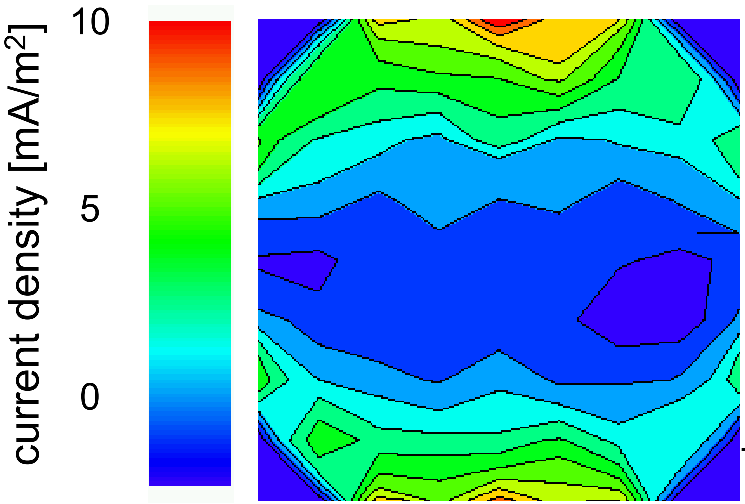


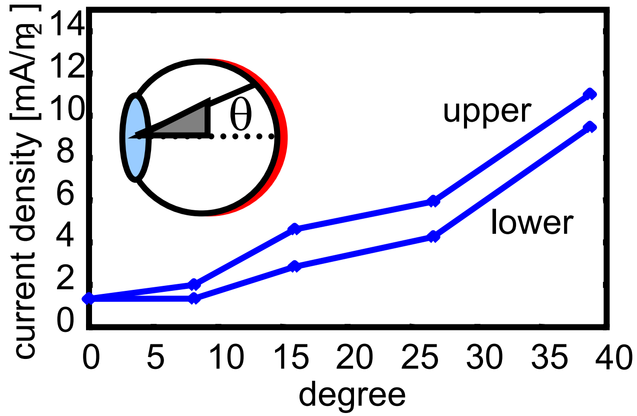
vertical section   horizontal section
near eyes

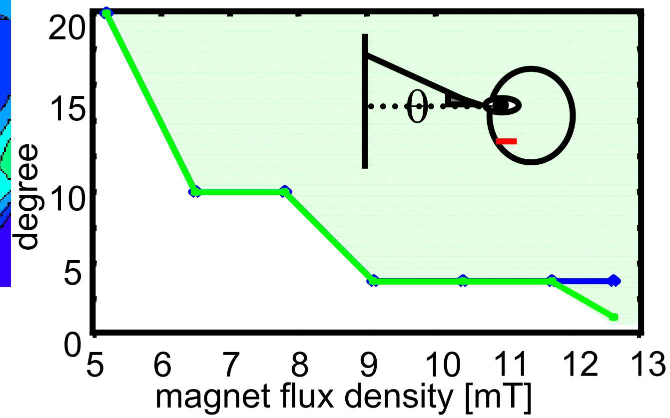
From Kanako Wake

Induced Current in Retina









- Larger in the upper and lower part of retina
  - Consistent with reported experience of subjects
- Maximum J in retina ~11 mA/m^2
  - Reported threshold current density for electrical stimulation to excite retinal cells 10 mA/m^2 (Knighton, 1973)

Comparison with Electrophosphene (2D FEM)

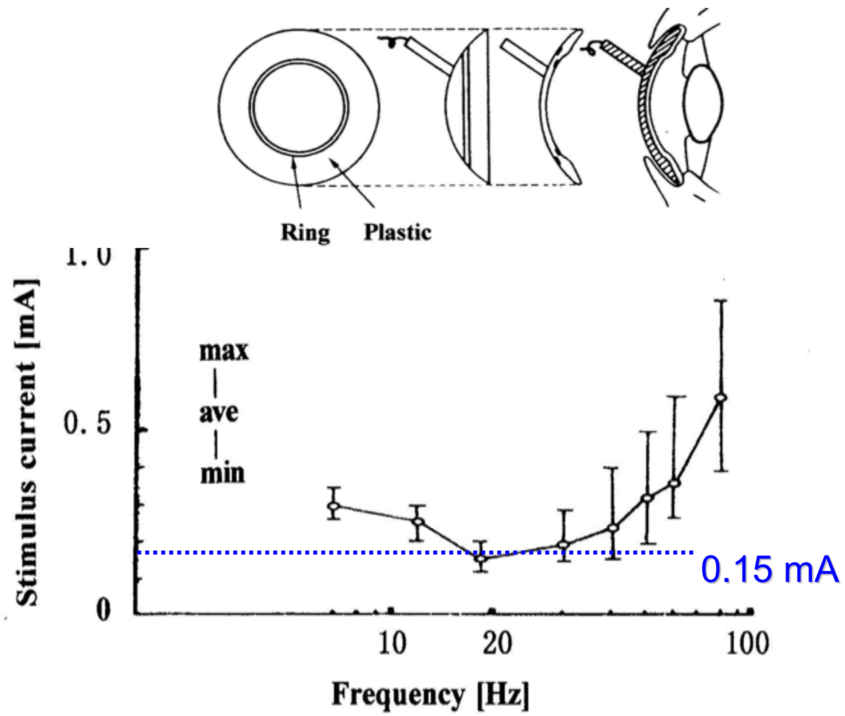


Fig. 2 Thresholds of electrophosphene

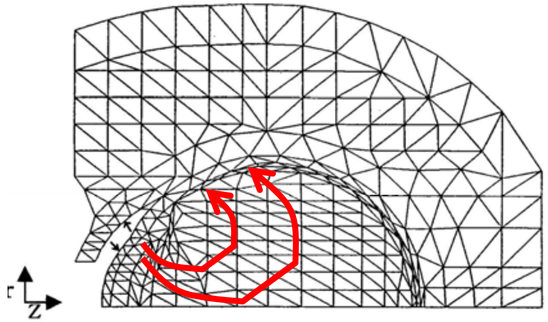


Fig. 3 Eye model with electric constants for FEM

Table 1 Electric constants for the eye model

	organs	conductivity S/m	relative permittivity
fat	under skin / in orbit	0.04	10^5
mu	sclera/zonules of Zinn/eyelid	0.13	10^6
nerv	retina / optic nerve	0.17	10^6
eyeball	cornea/lens/vitreous body	0.3	10^6
blood	choroid	0.55	10^6
fluid	anterior/posterior chamber	1.6	10^6
bone	orbital bone	0.006	10^6

Threshold current was 0.15 mA.
Estimated **electric field in retina is about 50 mV/m**.

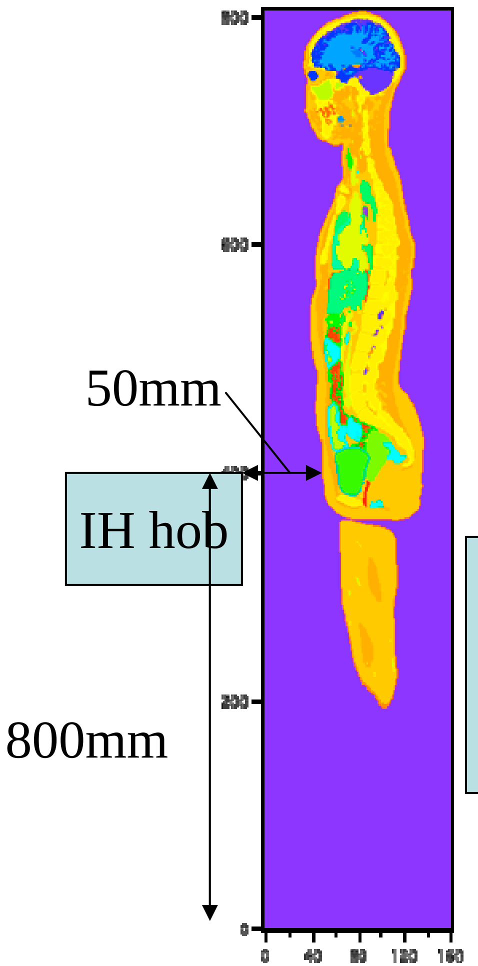
M.Kawasumi, M.Saito,K.Wake,M.Taki, 2000

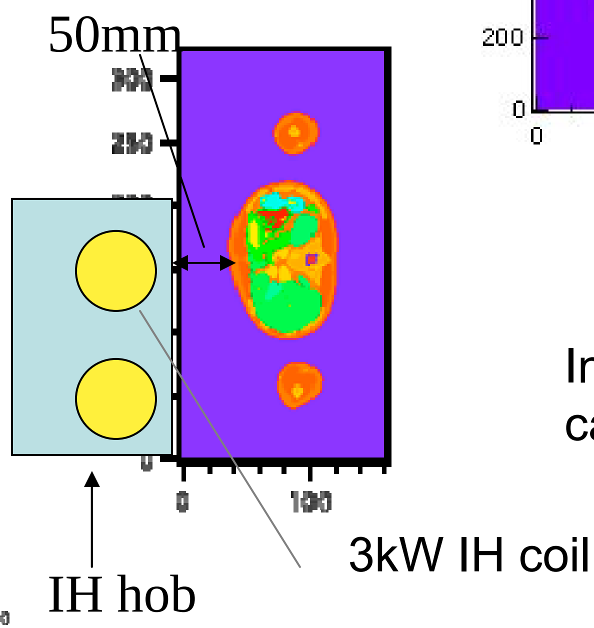
Examples of intermediate frequency (IF) dosimetry

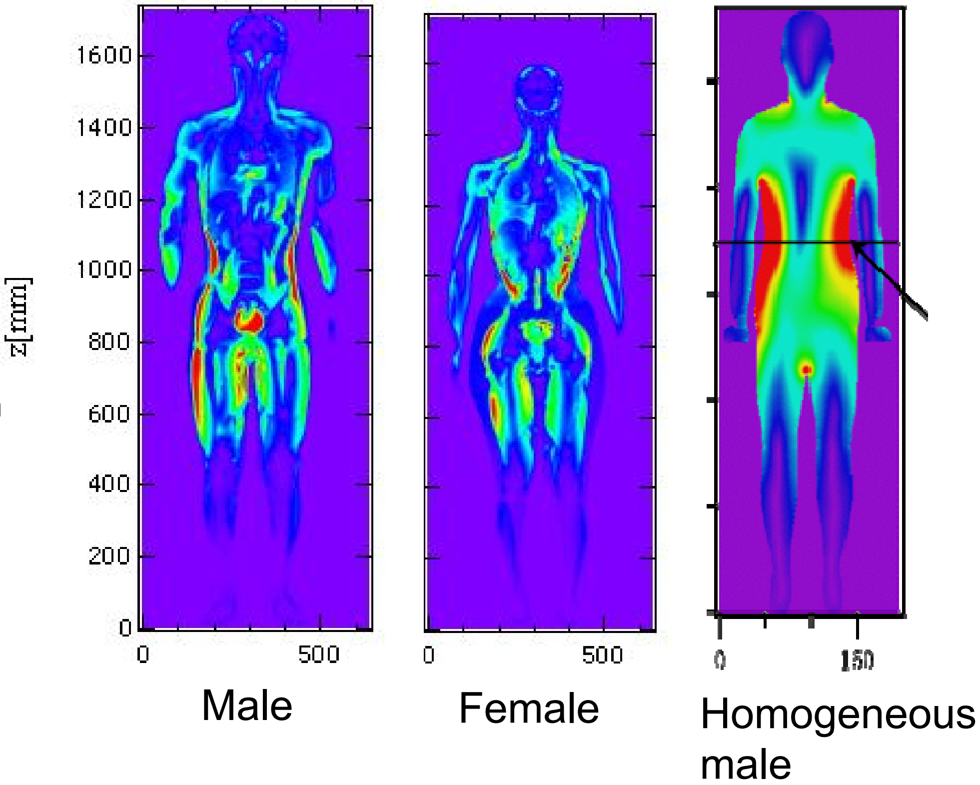
(1) 10 kHz – 100 kHz

Induction heating hob

20kHz for steel pan, 60-80kHz for aluminum pan







Induced current density distributions calculated by impedance method

From Y. Suzuki, et al

Contact current

- Contact current is limited with reference levels of ICNIRP guidelines

Table 5. Reference levels for time-varying contact currents from conductive objects.

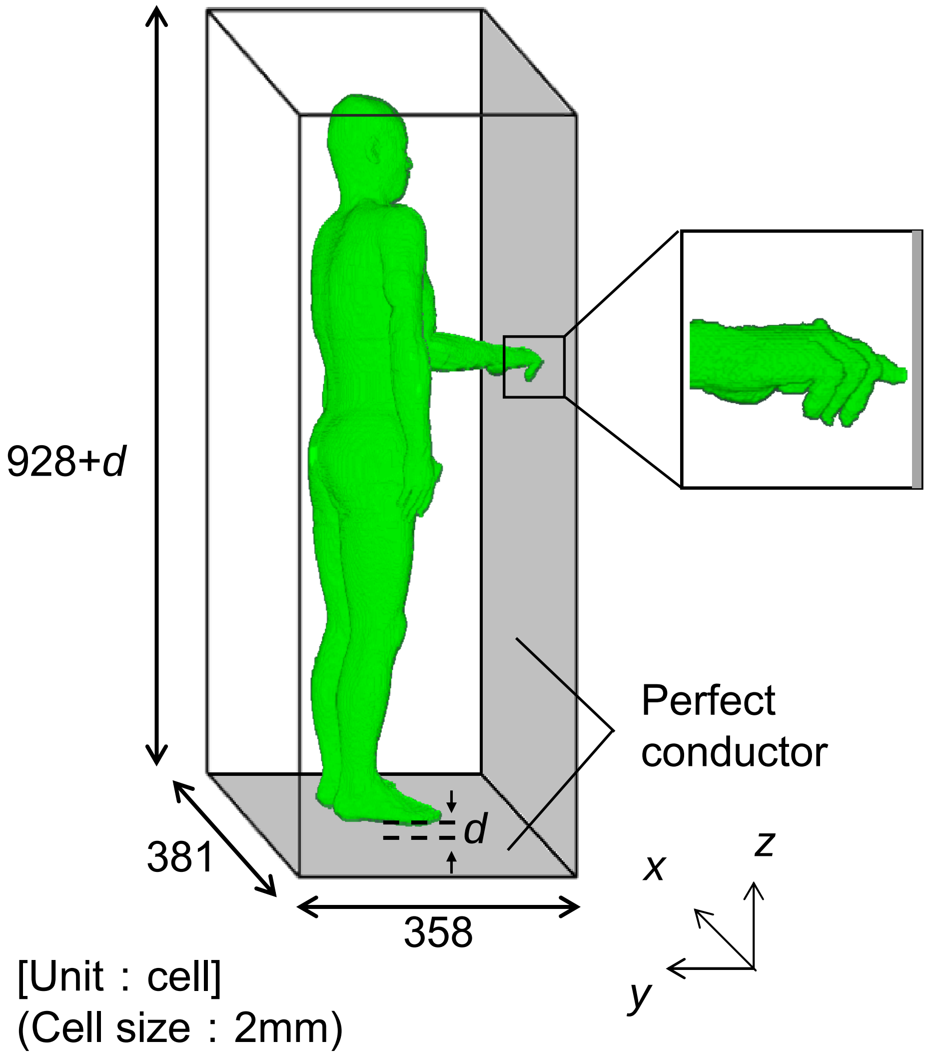
Exposure characteristics	Frequency range	Maximum contact current (mA)
Occupational exposure	Up to 2.5 kHz	1.0
	2.5–100 kHz	0.4*f*
	100 kHz–10 MHz	40
General public exposure	Up to 2.5 kHz	0.5
	2.5–100 kHz	0.2*f*
	100 kHz–10 MHz	20

Note: *f* is the frequency in kHz.

ICNIRP Guidelines 1Hz – 100 kHz (2010)

e.g. Contact current flows into human body by touching an ungrounded pan on IH hob.

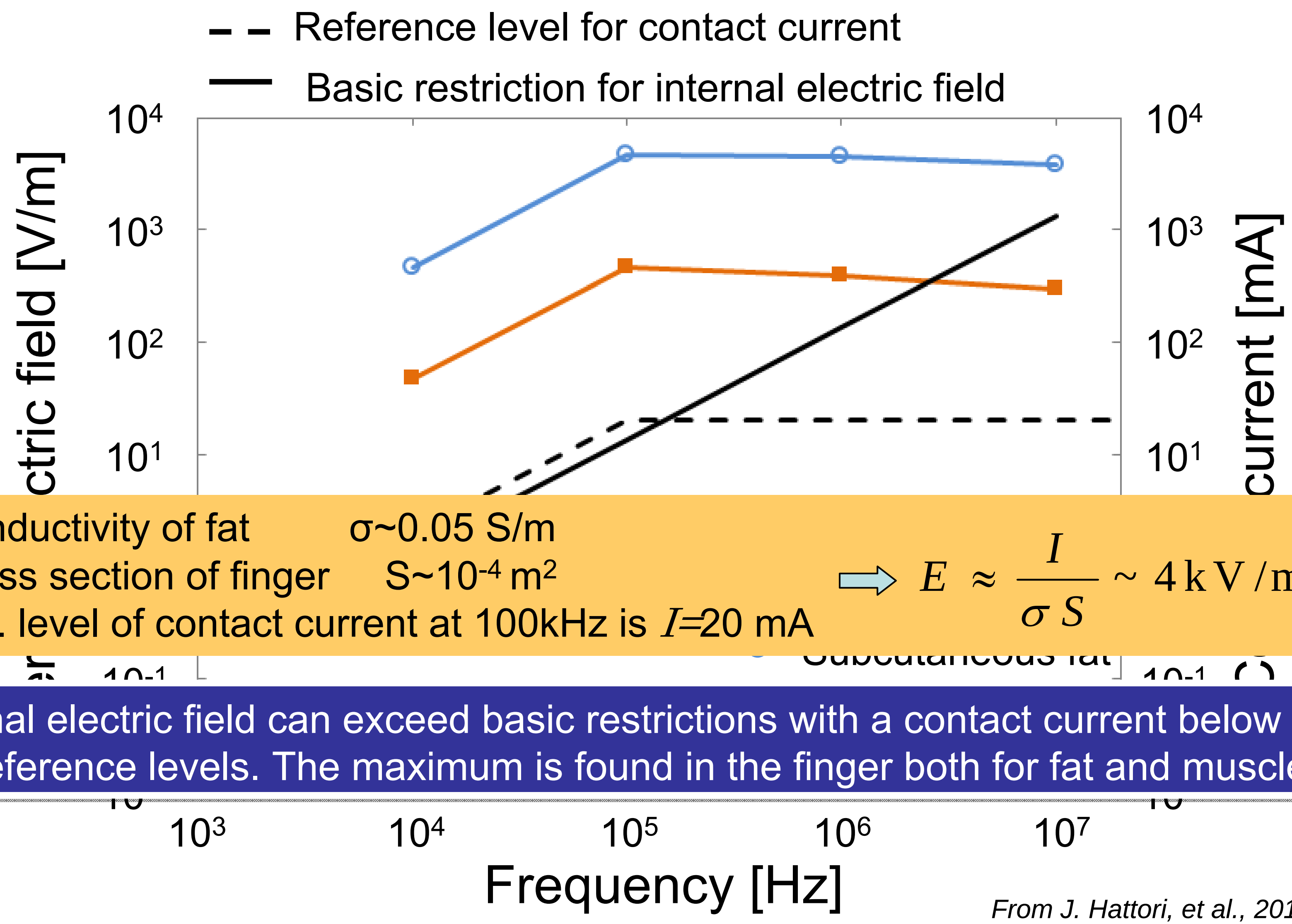
Contact current



- Internal electric field is estimated when contact currents of reference levels occur **on the finger**
- The results will be compared with the basic restrictions of ICNIRP guidelines (2010)
- Heterogeneous male human model TARO with 51 tissues
- Human body is grounded to estimate worst case (d=0)
- Quasi-static FDTD method
- 10 kHz – 10 MHz

From J. Hattori, I.Laakso, A. Hirata, Y. Suzuki, M. Taki, 2012

Maximum Internal electric field at the reference level of contact current



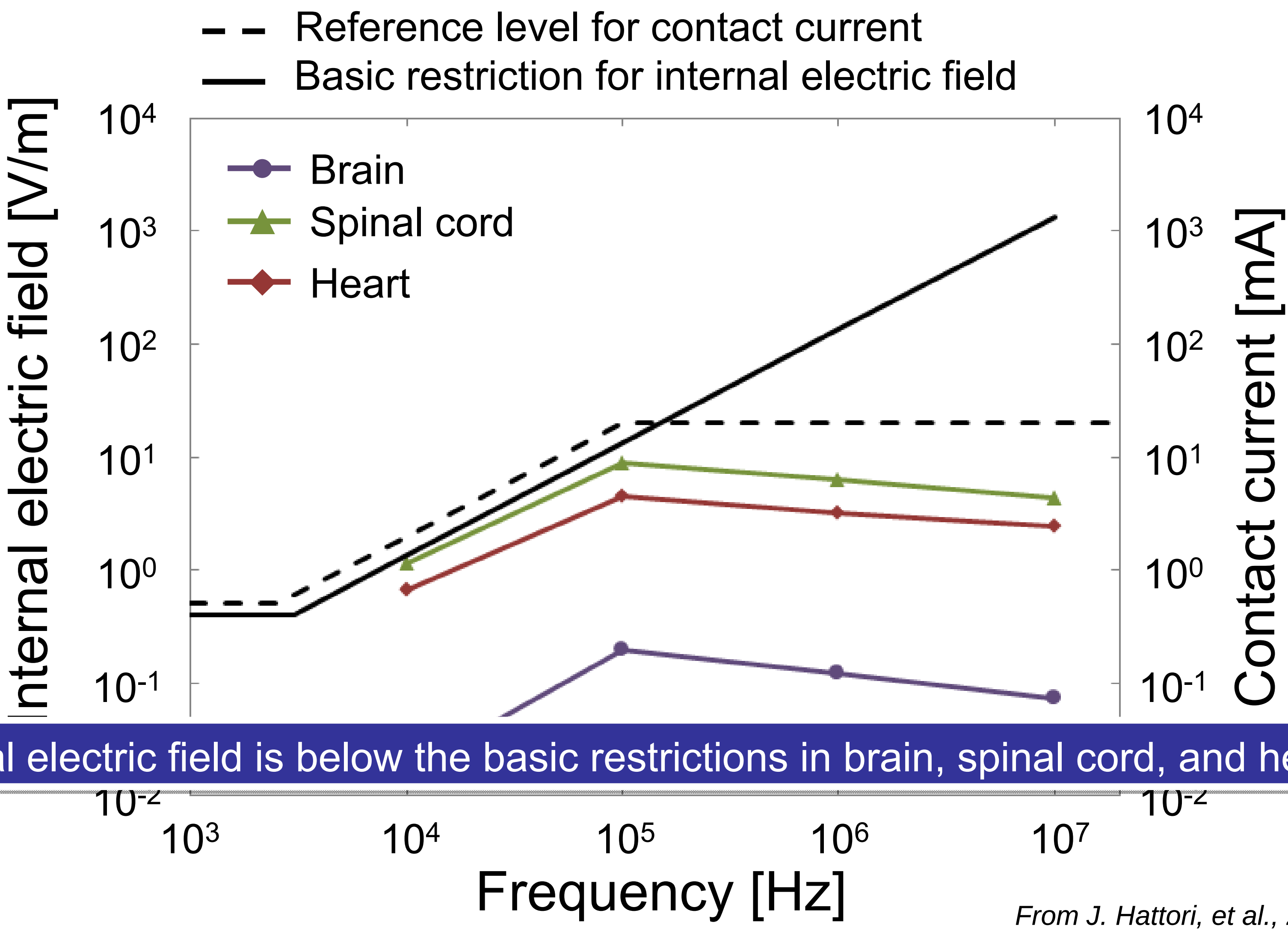
Conductivity of fat σ~0.05 S/m
Cross section of finger S~10^{-4} m^2
Ref. level of contact current at 100kHz is I=20 mA

$$\Rightarrow E \approx \frac{I}{\sigma S} \sim 4\,\mathrm{kV/m}$$

Internal electric field can exceed basic restrictions with a contact current below the reference levels. The maximum is found in the finger both for fat and muscle.

From J. Hattori, et al., 2012

Maximum Internal electric field at the reference level of contact current



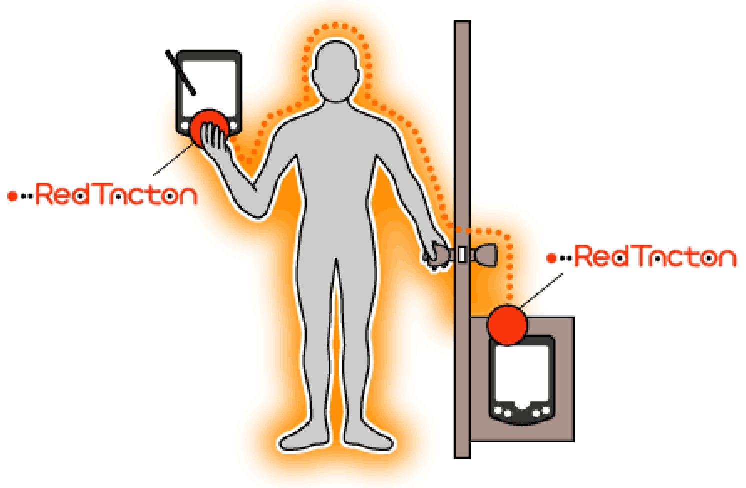
Internal electric field is below the basic restrictions in brain, spinal cord, and heart.

From J. Hattori, et al., 2012

Examples of IF dosimetry (1- 10 MHz)

Intra-body communication device

- The terminal transmit electric near field around 5 MHz.
- The electric field couples to human body quasi-statically.
- The receiver detects the electric potential induced through human body.



RedTacton (NTT) 10.7MHz

Zimmerman 1995

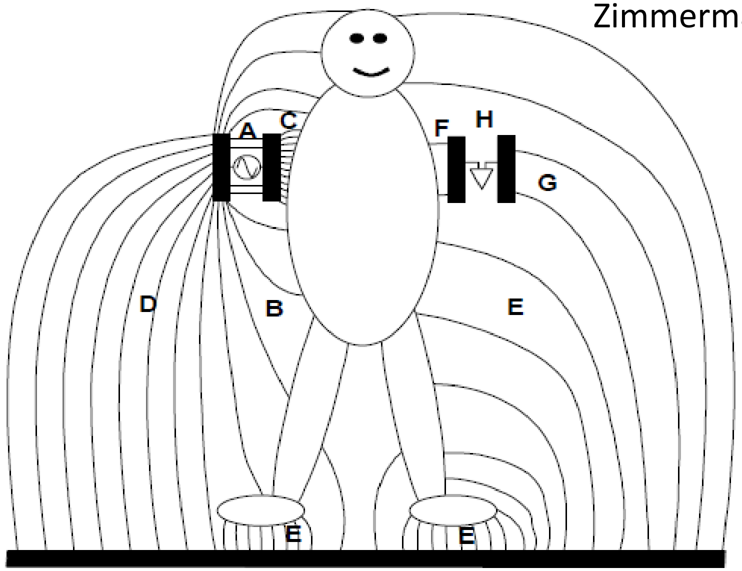
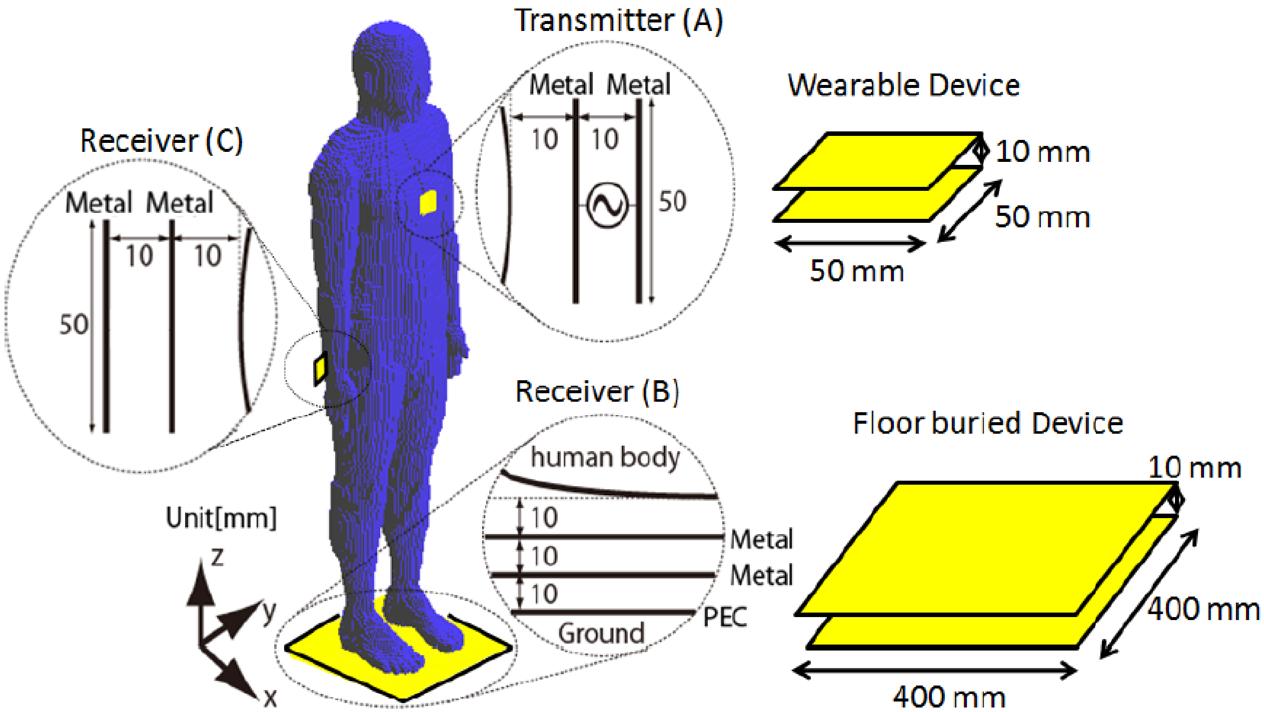


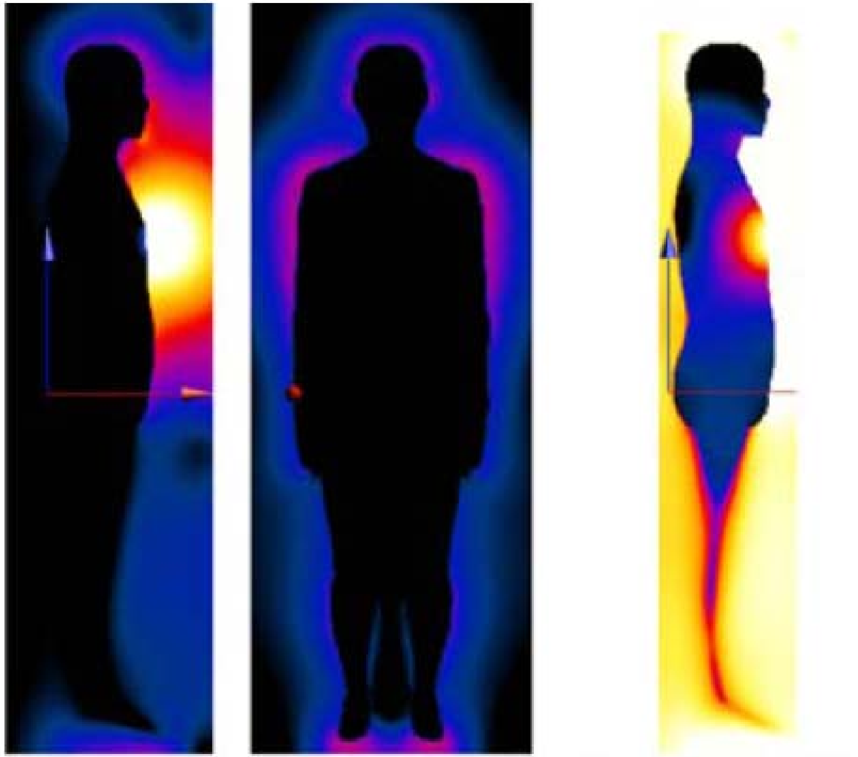
Figure 3. Electric fields produced by PAN transmitter T. A small portion of the electric field G reaches the receiver R.

Model and method for numerical dosimetry

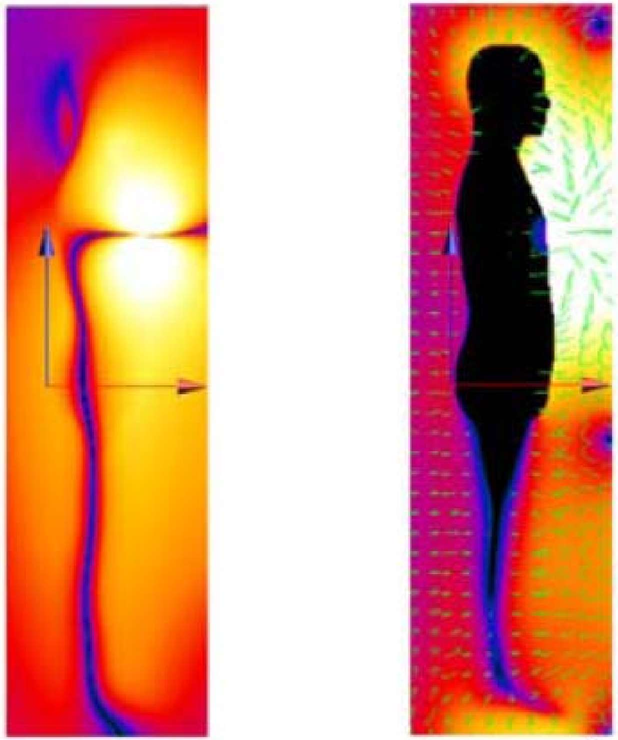


- **Full-wave calculation of FDTD method** was employed in spite of quasi-static nature of the field of 5 MHz (time consuming computation but feasible).
- External magnetic field is of interest as emission below 30 MHz is measured by loop antennas according to the standard measurement procedure.

Calculated results of internal and external fields

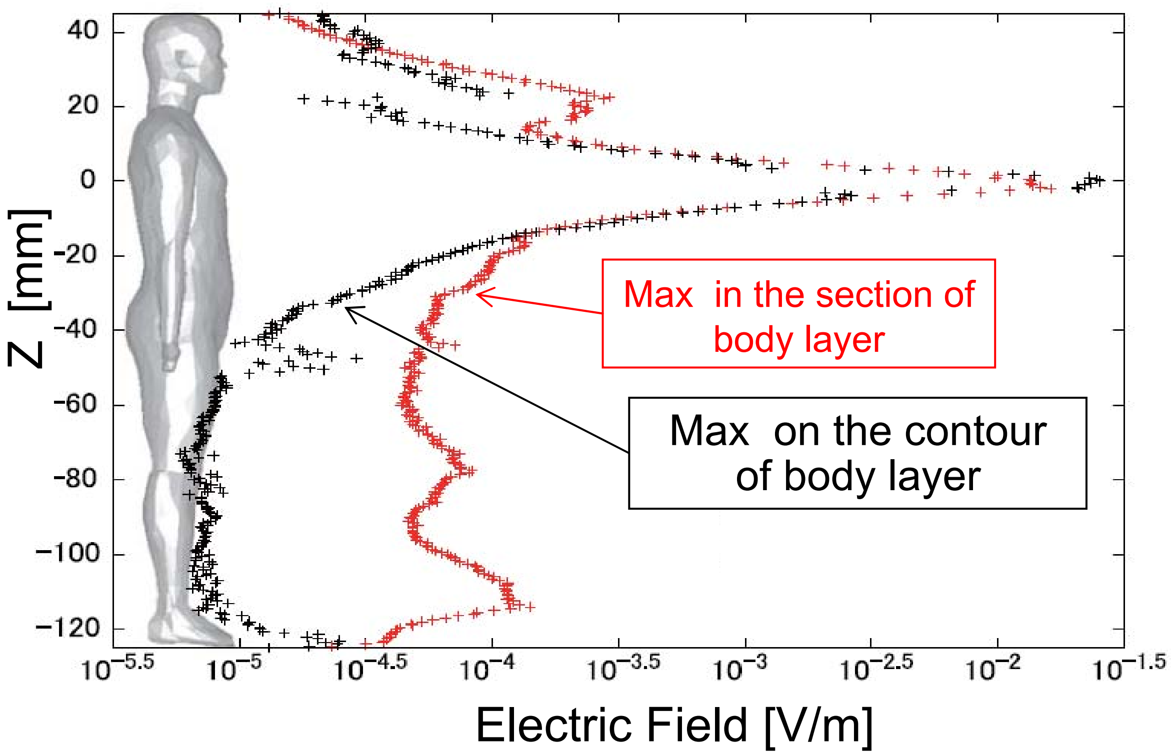


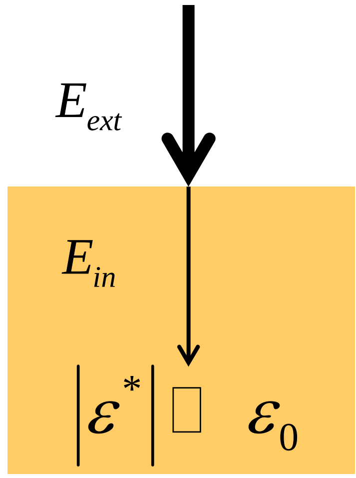
Electric field



Magnetic field

Simple method to identify maximum internal field





$$\left|E_{in}\right| \approx \frac{\varepsilon_0}{\left|\varepsilon^*\right|}\left|E_{ext}\right|$$

- A simple method is applicable to estimate maximum internal field or SAR.
- External field is first obtained with human model replaced by perfect conductor.
- Internal electric field is then estimated from the surface electric field.

Wireless power transfer system

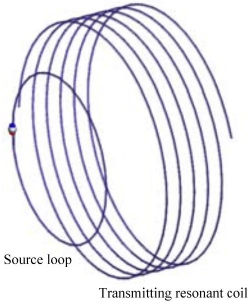
- Resonance type wireless power transfer was proposed in 2007.
- The technology have attracted attention owing to the high transfer efficiency

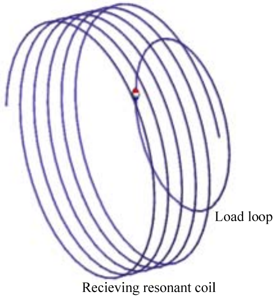
http://web.mit.edu/newsoffice/2007/wireless-0607.html

- Limitation due to safety requirement is a matter of concern in the development of the system
- There was a misunderstanding about safety of magnetic field exposure in the early stage

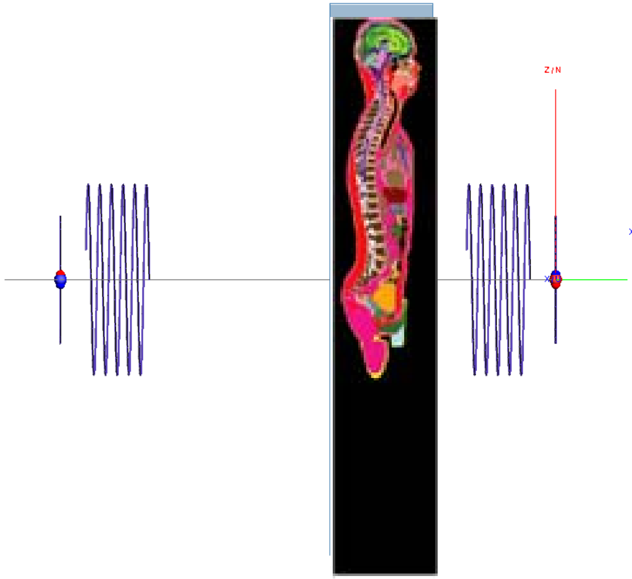
Simulation model

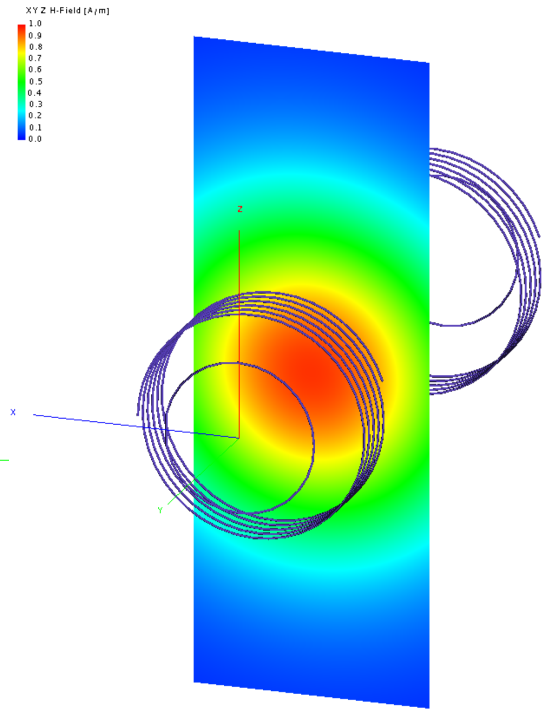
Resonance frequency: 10 MHz
Power efficiency: about 92 %



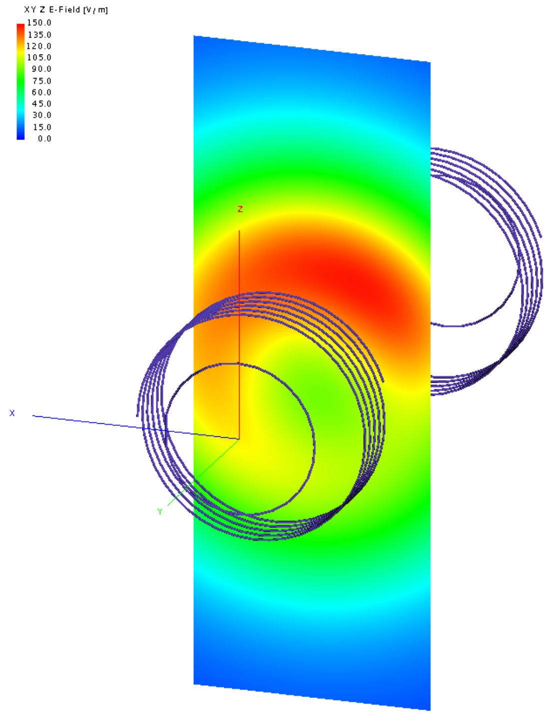


Dosimetry





Magnetic field distribution

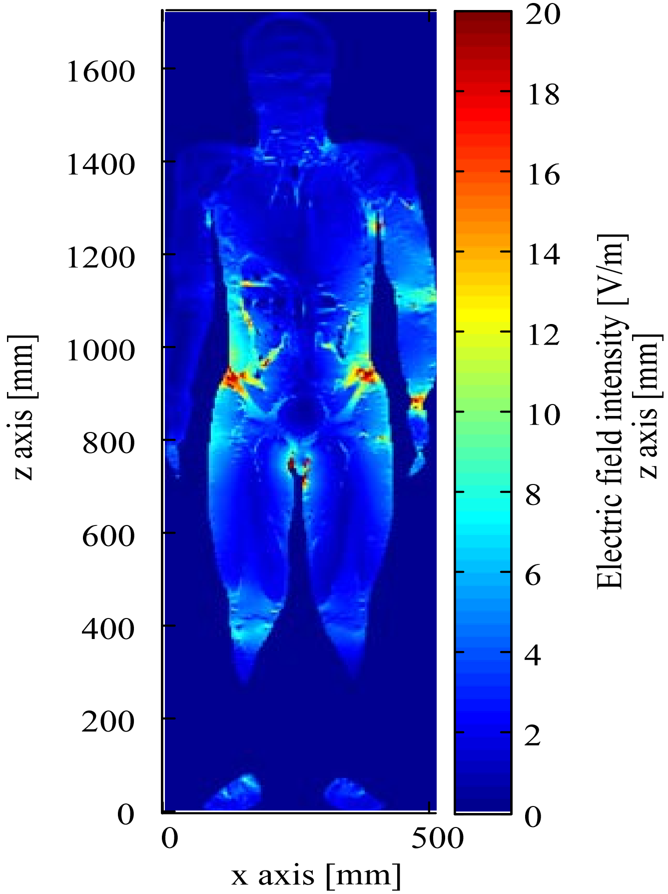


Electric field distribution

- Incident electric and magnetic fields are calculated with method of moment (MoM).
- SAR is calculated by two different method
  - **Impedance method** with taking **only magnetic field** exposure into account.
  - Full wave analysis of scatter-field **FDTD method** taking **both electric and magnetic field** exposure into account

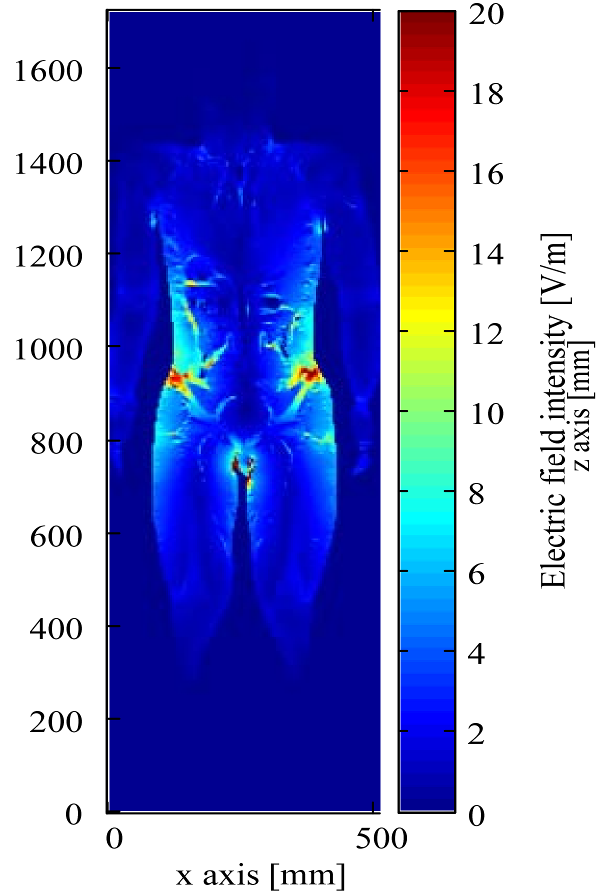
From SangWook Park, Kanako Wake, and Soichi Watanabe

Induced electric field



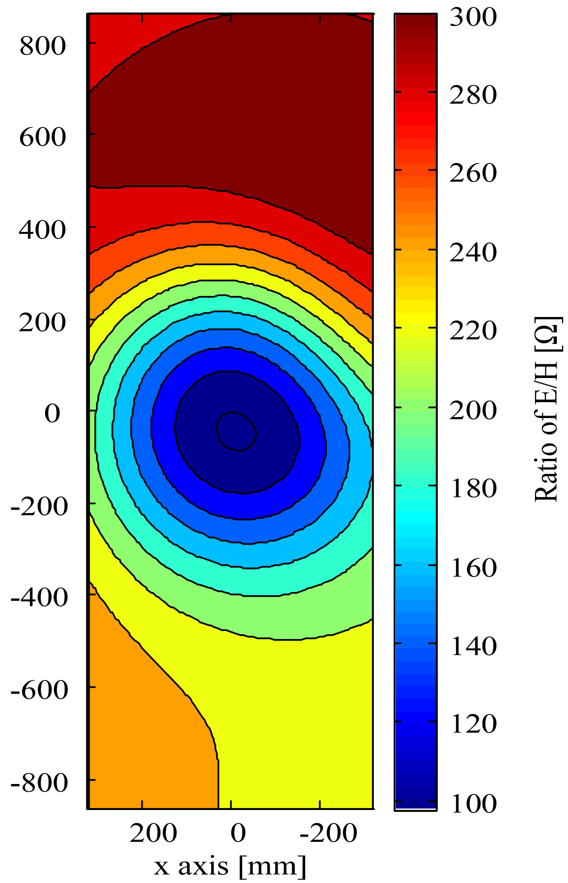
FDTD method

Both E and B



Impedance method

Only **B**



Ratio E/H

From SangWook Park, Kanako Wake, and Soichi Watanabe

Dosimetry results for input power of 1 W

	FDTD (Tissue)	Impedance (Tissue)	Difference [%]
E_{99}	14.44 (Fat)	14.29 (Fat)	1.04
E_{99cns}	2.83 (Nerve)	1.12 (Nerve)	60.39
SAR_{10g}	2.96e-2 (Skin)	2.96e-2 (Skin)	0.33
SAR	1.36e-3	9.37e-4	31.39

Notes:

- E_{99} is the 99th percentile value of the electric field [V/m].

- E_{99cns} is the 99th percentile value of the electric field in central nervous system (CNS) tissue [V/m].

- SAR_{10g} is the localized SAR averaging of any 10g of contiguous tissue [W/kg].

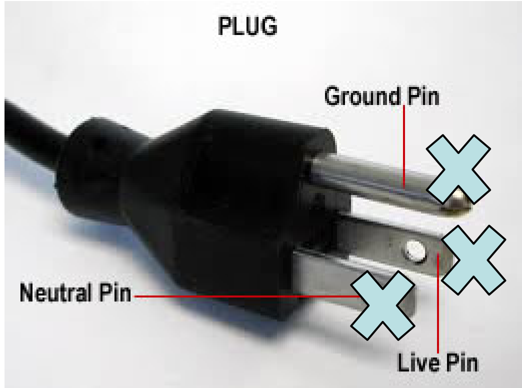
- SAR is the whole-body average SAR [W/kg].

Electric fields are not negligible in the high ratio E/H even if the coupling is made with magnetic field

From SangWook Park, Kanako Wake, and Soichi Watanabe

Remarks on ELF/IF dosimetry

- Quasi-static approximation is applicable up to about 10 MHz.
- Quasi-static nature of field allows intuitive understanding of internal field distribution
  - Simple estimation of maximum internal electric field from surface electric field (intra-body communication device)
- Even if the application apparently uses only magnetic field, electric field should not be ignored (e.g. IH hob, magnetic resonance type wireless power transfer system)
- Contact current should be assessed in application of ELF/IF electromagnetic field.



MILLIMETER-WAVE DOSIMETRY

Dosimetric quantities for MMW

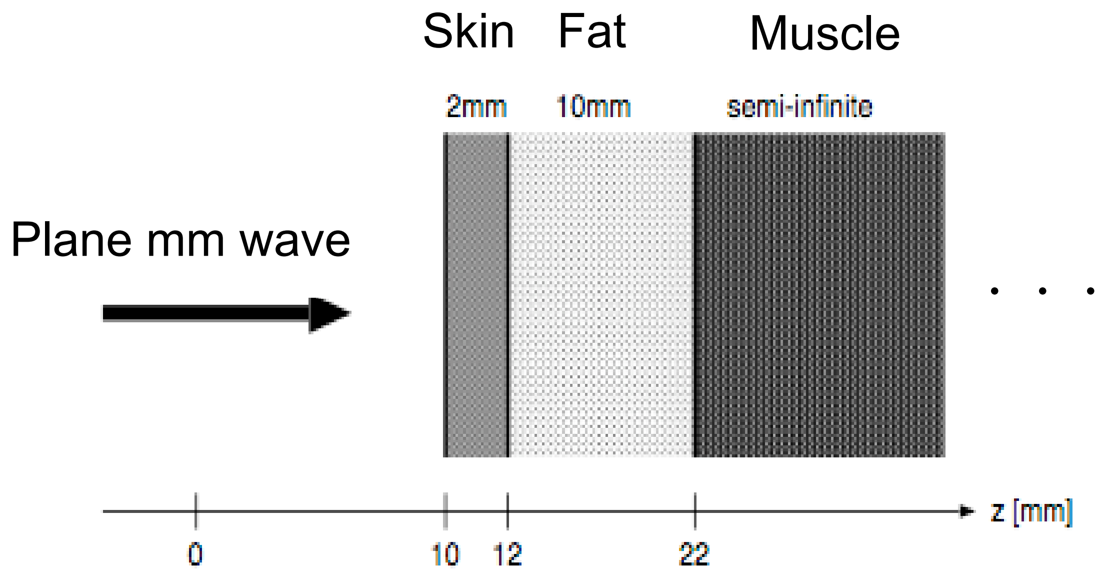
- ICNIRP guideline (1998) provides basic restriction for MMW in terms of **incident power density** [mW/cm^2]
- Interaction occurs mainly on the surface of the body (skin/eye).
- Is it no use for us to consider internal events due to exposure to MMW?

→ **Answer is NO! We should consider**

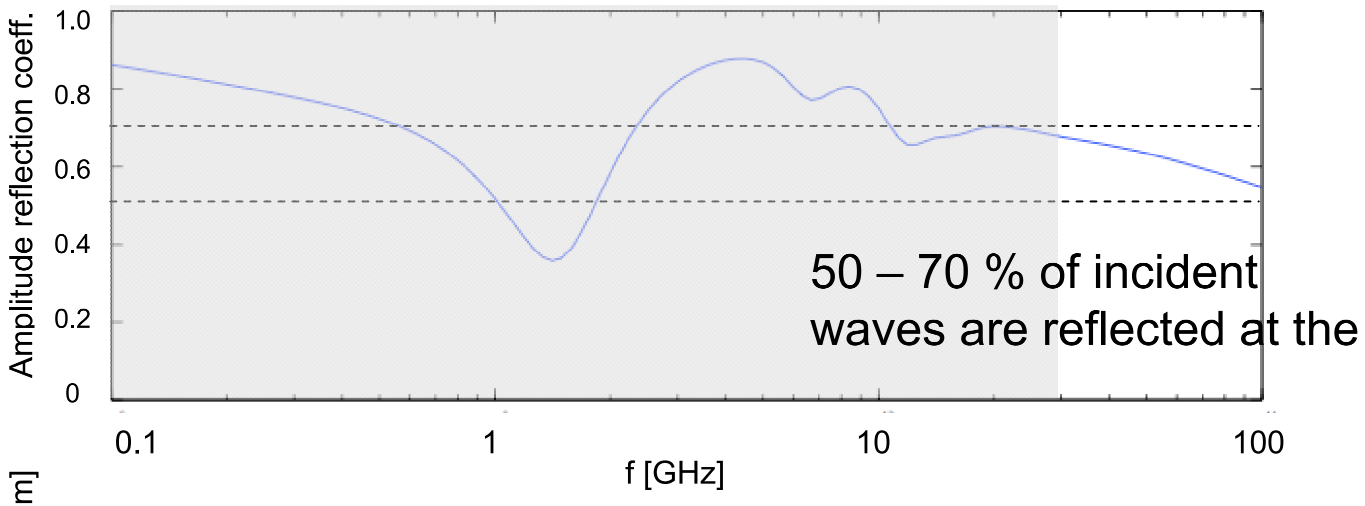
  - **Reflection at the surface**
  - **Temperature elevation in tissue**

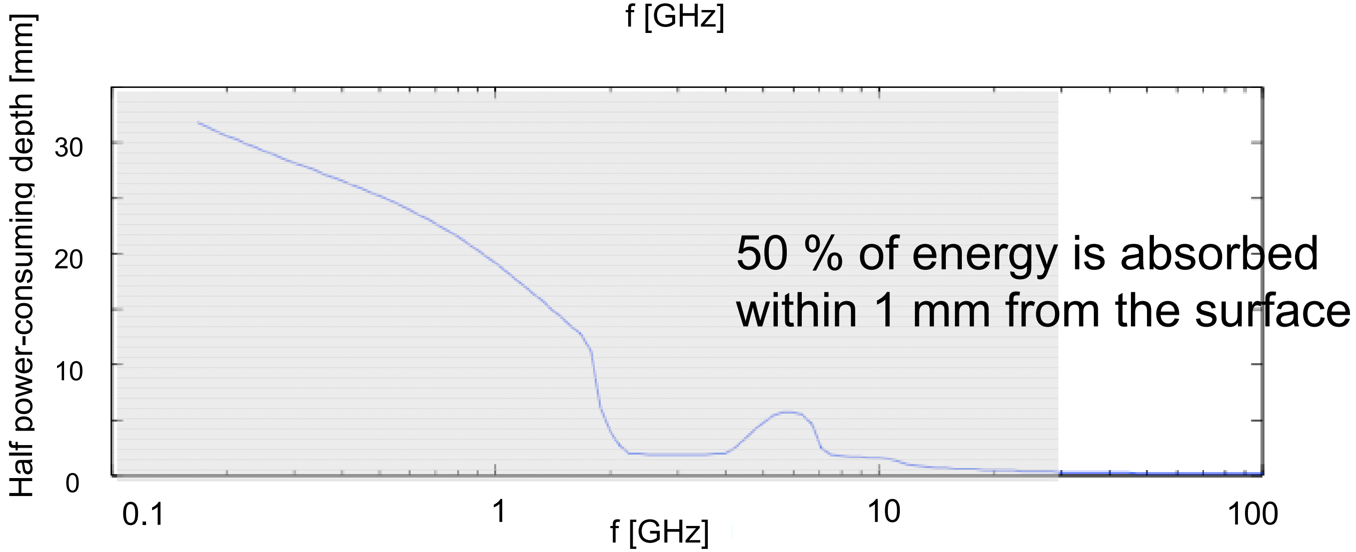
Analysis of reflection and absorption with 3-layer model

- Amplitude reflection coefficient and the depth where cumulative absorbed energy in $z<z_0$ become 50 % are calculated with one-dimensional model.
- Dielectric constants were extrapolated from Gabriel's report.
  (Dielectric Properties of Body Tissues, Italian National Research Council, http://niremf.ifac.cnr.it/tissprop/)



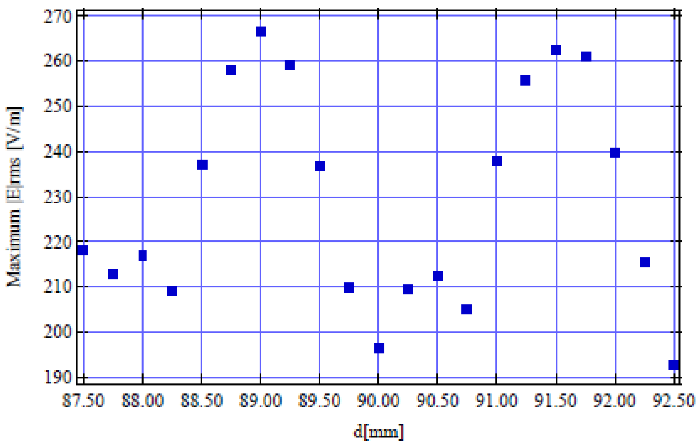
Amplitude reflection and power absorption by 3-layer tissue

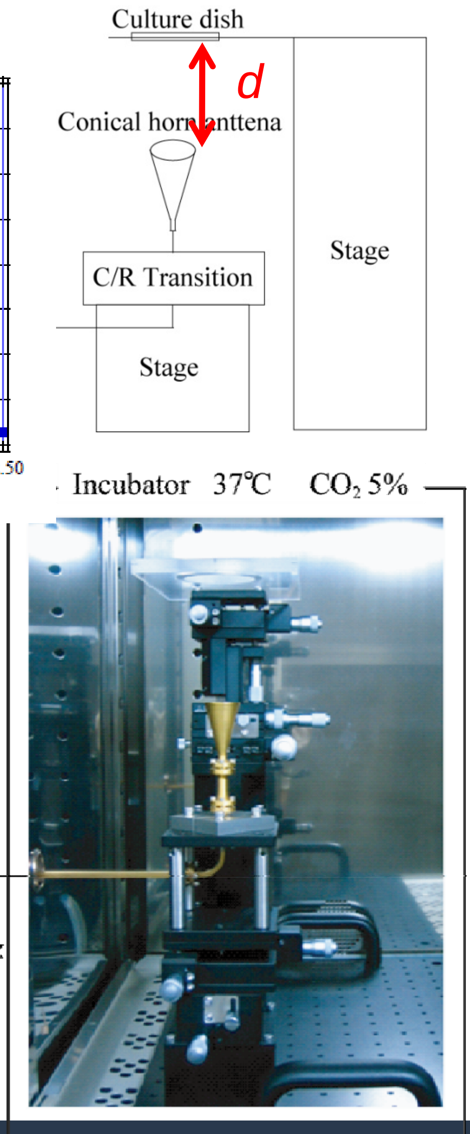




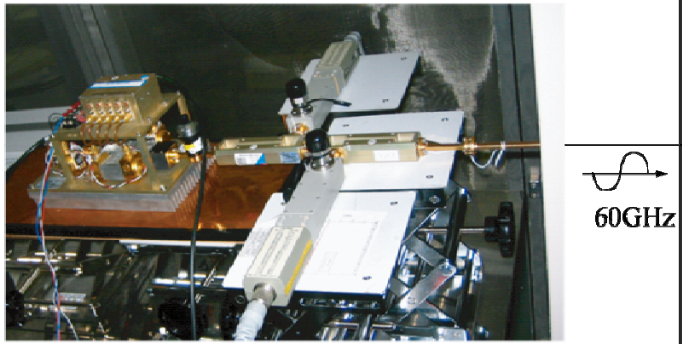
Data by Prof. Nishikata

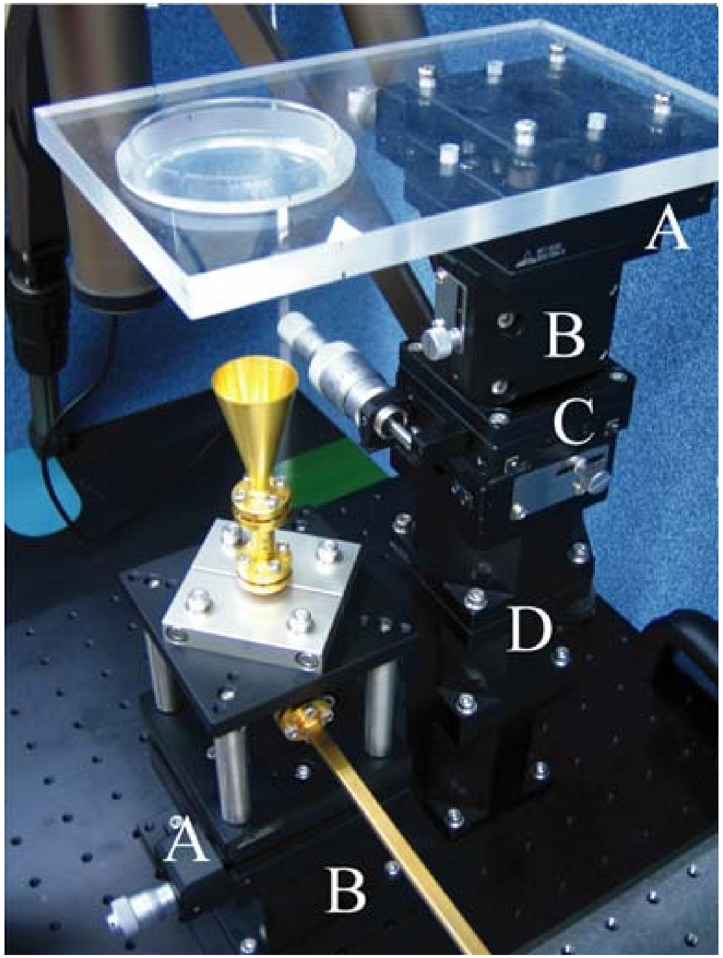
Composition of the Apparatus



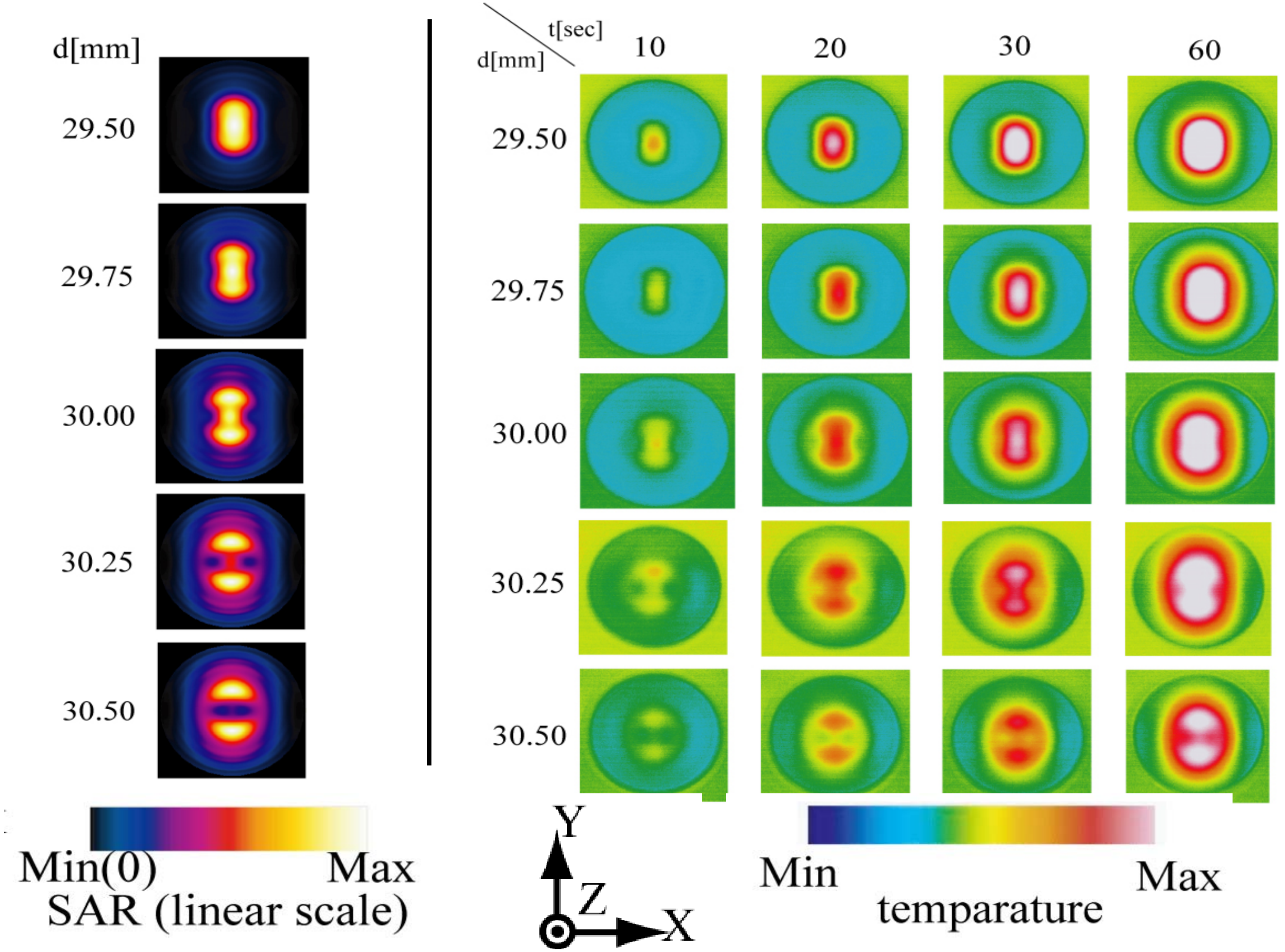


36% variation of E due to standing waves, resulting in about 90 % variation of SAR





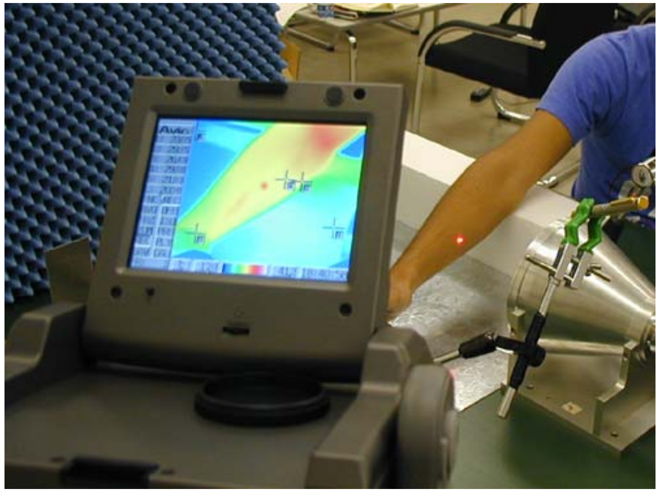
SAR distribution on the bottom of culture dish

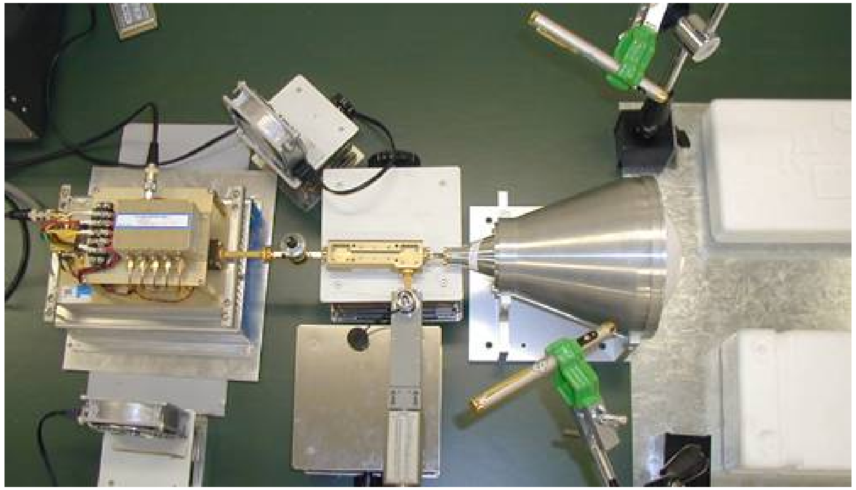


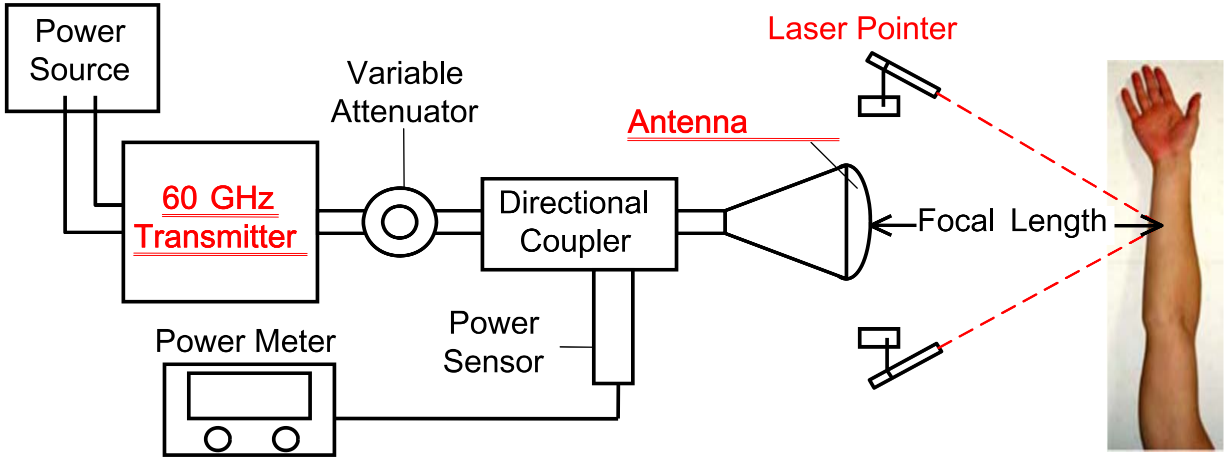
Calculated

Measured by thermograph camera

Measurement of warmth sensation

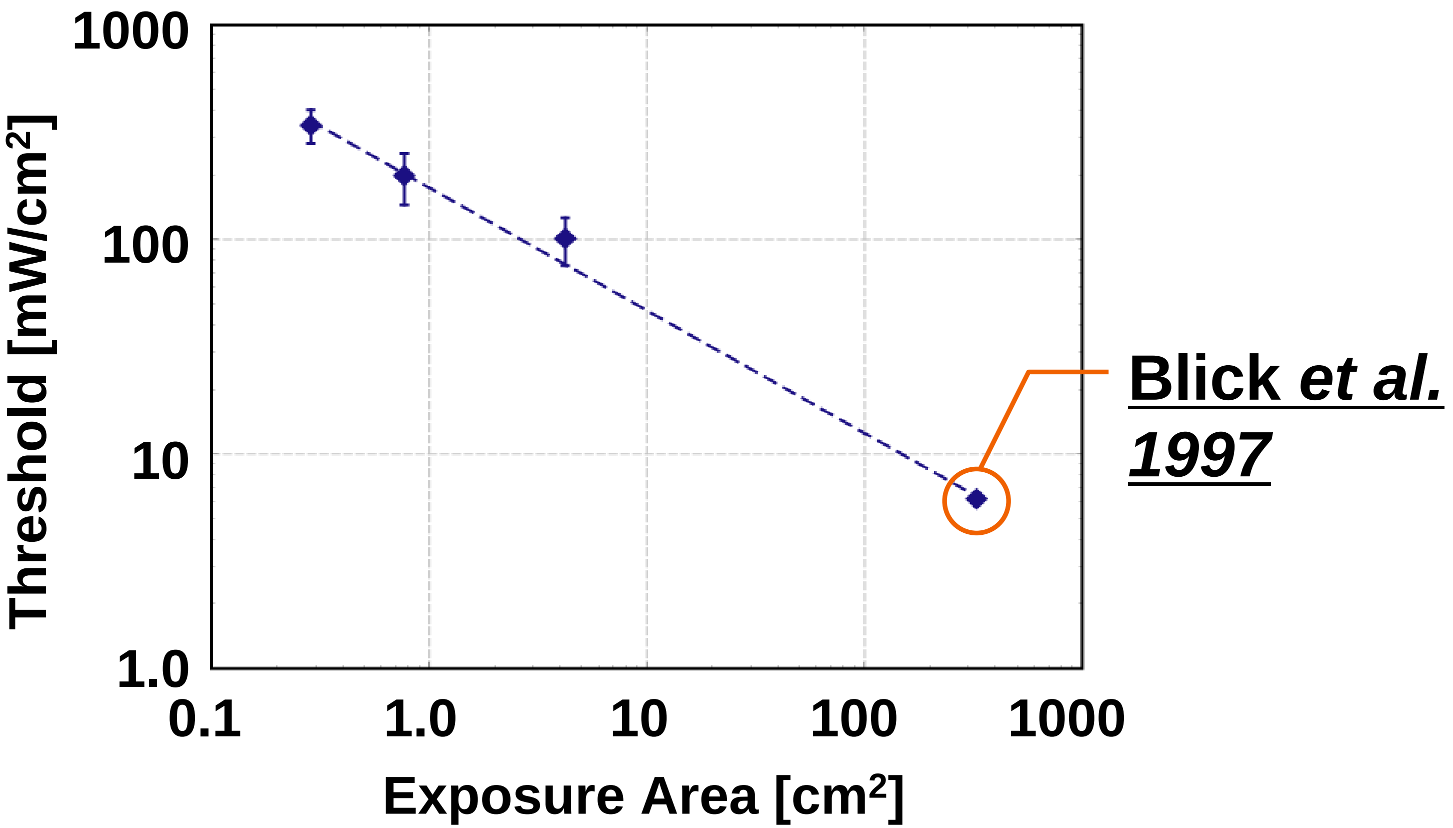






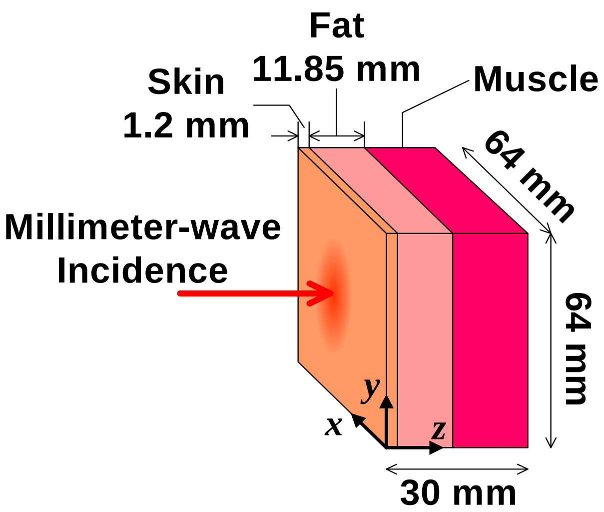
S. Watanabe, et al. 2006

Threshold of Warmth Sensation. Dependence on exposure area



S. Watanabe, et al. 2006

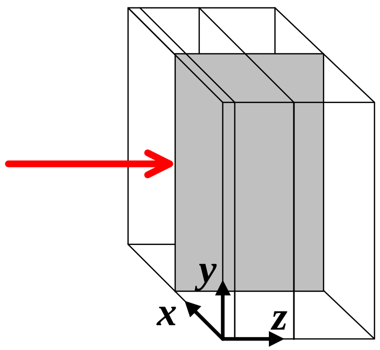
Dosimetry

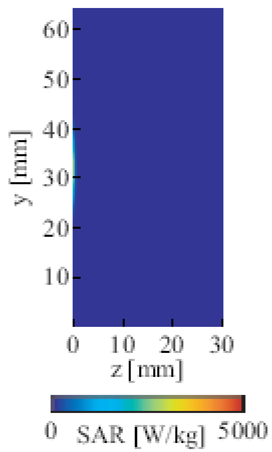


$$c\rho\frac{\partial T}{\partial t}=\nabla\cdot(\kappa\nabla T)-b(T)\,(T-T_b)+\rho\cdot\mathrm{SAR}$$

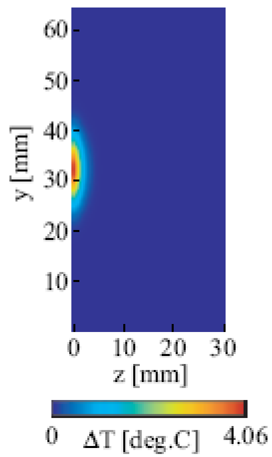
where

$$b(T)\propto 8.01T_b+0.85T-321.3$$



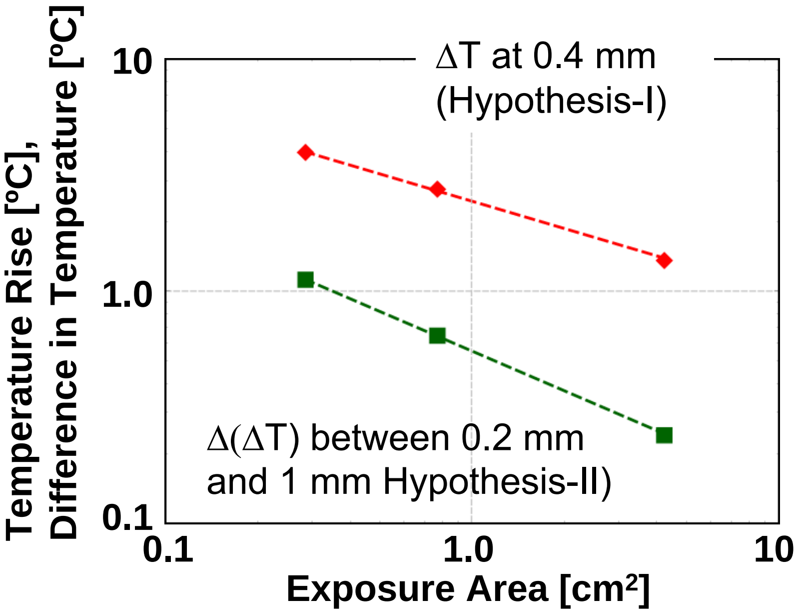


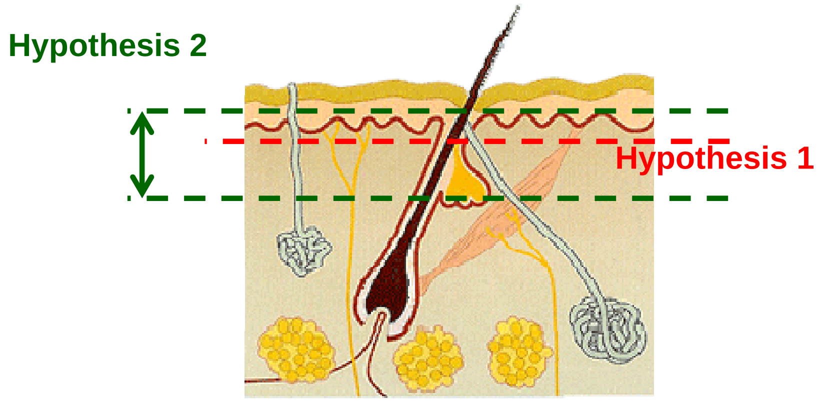
SAR distribution

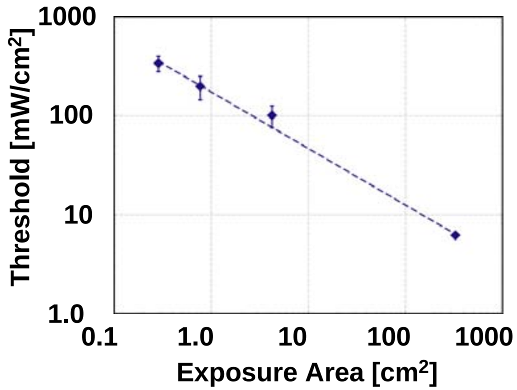


Temperature distribution

Discussion of warmth sensation threshold







ΔT at 0.4 mm = $2.4\ A^{-0.39}$

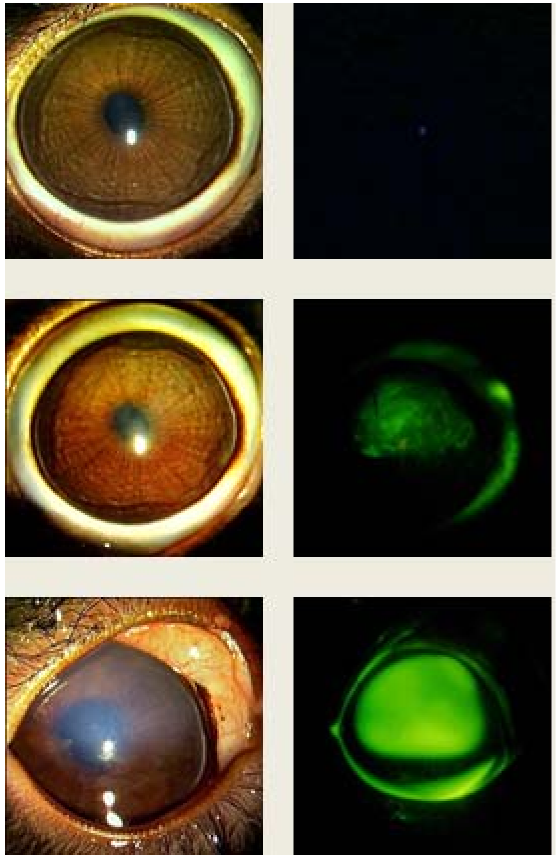
ΔT from 0.2 mm to 1 mm = $0.55\ A^{-0.57}$

$$P_{th} = 174\ A^{-0.57}$$

S. Watanabe, et al. 2006

Dosimetry for experiment on ocular effect

- Effect on rabbit eye of 40GHz, 60GHz, 75GHz, and 95GHz MMW
- Corneal damage due to thermal effect
- Dependency on strength and duration of exposure duration



Before exposure

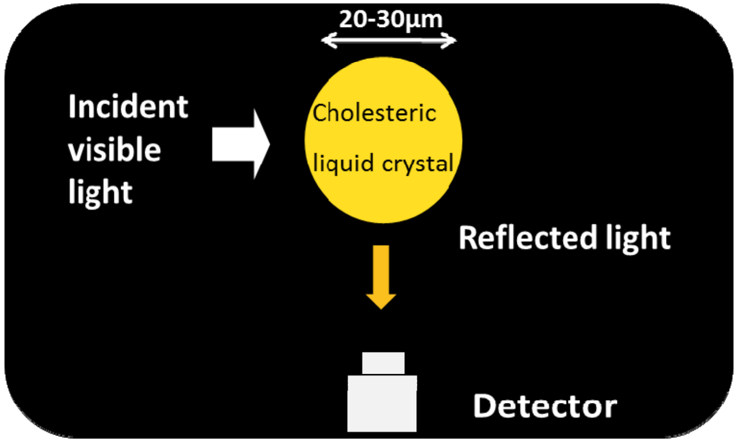
Immediately after exposure

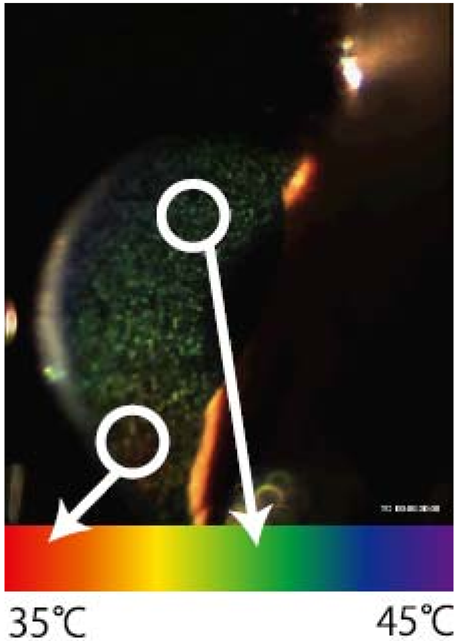
1-day after exposure

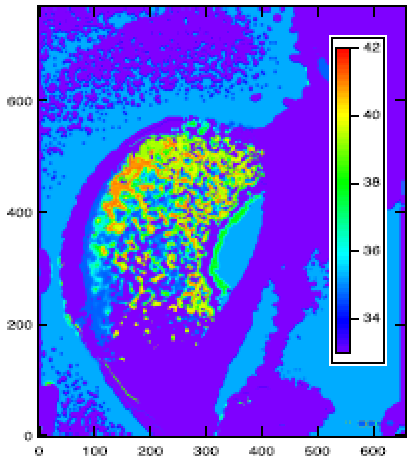
By M. Kojima and H. Sasaki

Experimental dosimetry

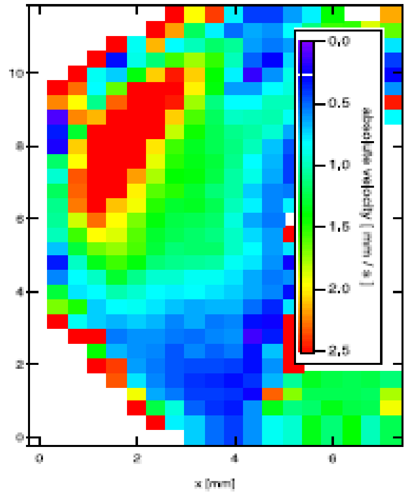
- Micro-Encapsulated Thermo-chromic liquid Crystal (MTLC)
- Imaging of temperature
- Imaging of velocity distribution using Particle Image Velocimetry (PIV) method







Distribution of temperature elevation in the anterior chamber



Distribution of velocity of aqueous humor in the anterior chamber

From Y. Suzuki

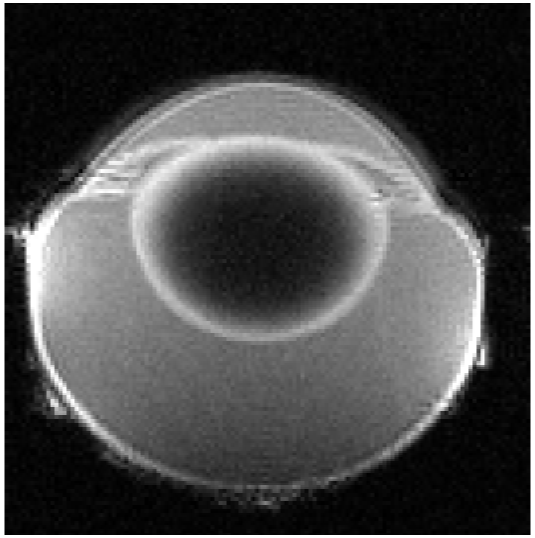
Effect of convection

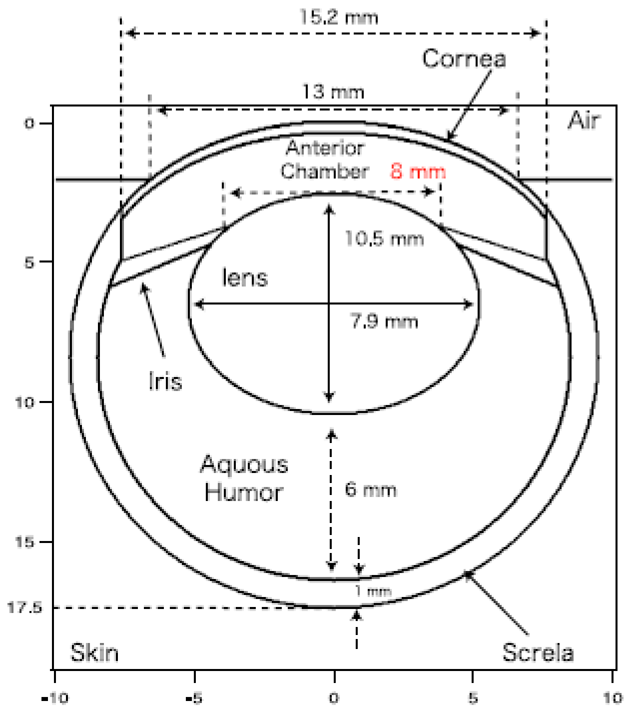
75 GHz, 200 mW/cm^2

From M.Kojima, H.Sasaki, Y.Suzuki

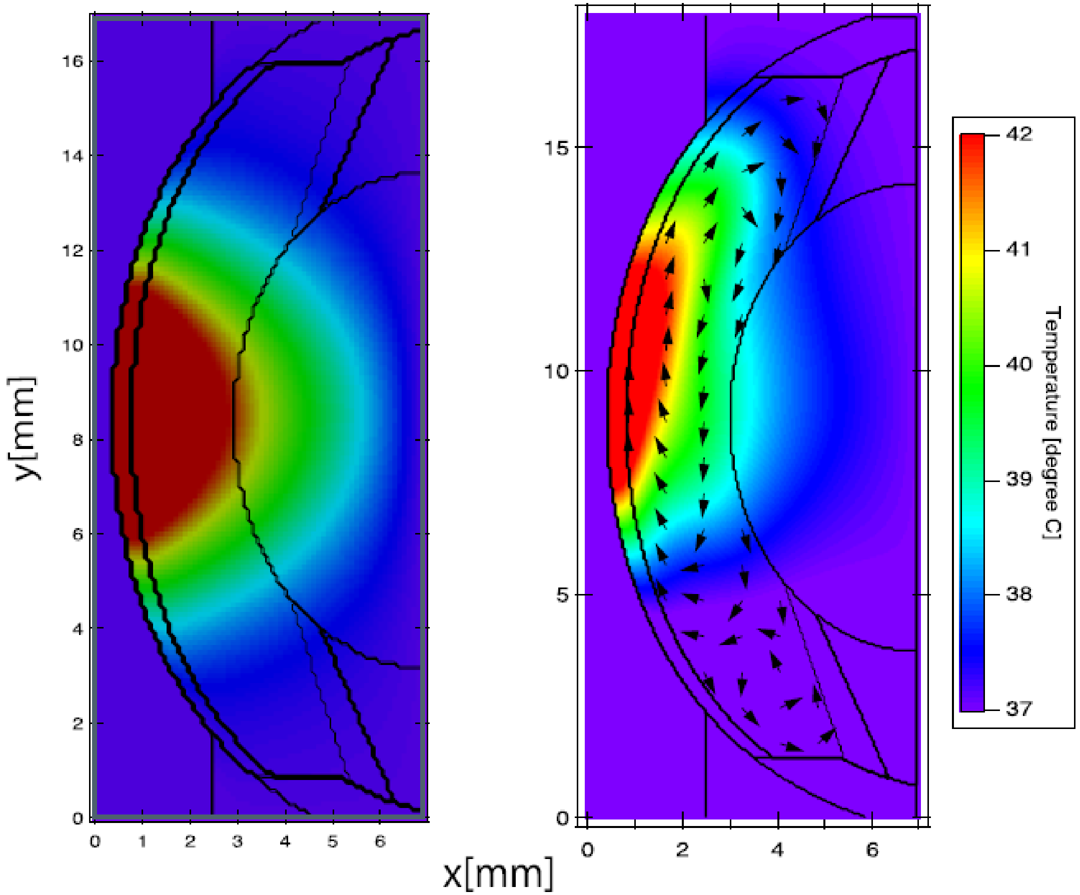
Computational dosimetry

- Modeling of incident waves
  - Measurement of E-field distribution in a plane
  - Reconstruction of MMW beam by Plane Wave Synthesis (PWS)
- Numerical rabbit eye model (0.1 mm and 0.05 mm resolution)
- Electromagnetic field analysis by FDTD method
- Numerical analysis of fluid dynamics by SMAC (Simplified Marker And Cell) method
- Thermal analysis





Simulation result of temperature distribution



Without convection

With convection

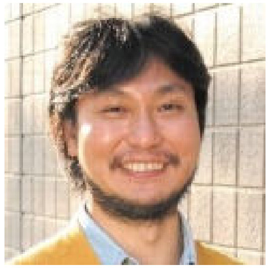
From A. Koike and Y. Suzuki

Remarks on MMW dosimetry

- Dosimetric quantity in MMW in the exposure guidelines is incident power density, which is a quantity outside of the body. However, dosimetry is still important to understand the interaction between MMW and human body.
- **Reflection** should be taken into account.
- **Temperature elevation in time and space** is the key physical quantity. Thus thermal analysis is crucially important.

Acknowledgment

- Tokyo Metropolitan University
  - Prof. Yukihisa Suzuki
  - *Many students*
- NICT
  - Dr. Soichi Watanabe
  - Dr. Kanako Wake
  - Dr. SangWook Park
  - Dr. Kensuke Sasaki
- Nagoya Inst. Technology
  - Prof. Akimasa Hirata
- Tokyo Inst. Technology
  - Prof. Atsuhiro Nishikata
- Kanazawa Medical University
  - Prof. Hiroshi Sasaki
  - Prof. Masami Kojima
- *Other colleagues*







Thank you!