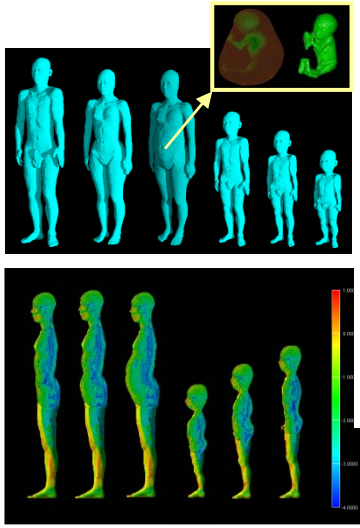

EMF Dosimetry (General methodology and RF region)

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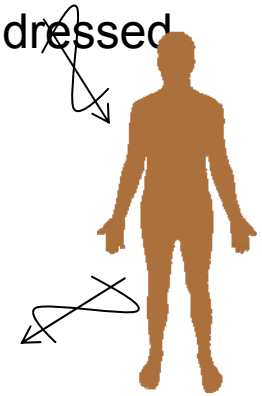
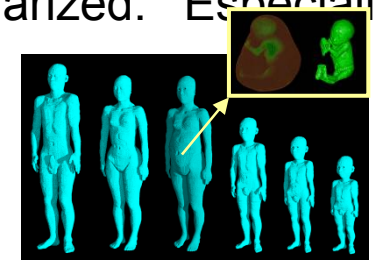
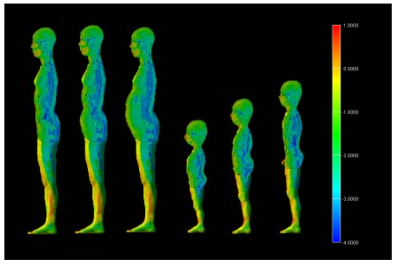
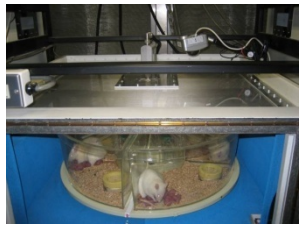
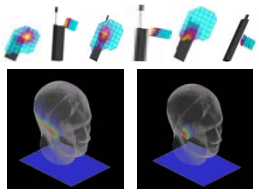
Introduction

Dosimetry is a term to represent "**evaluation of dose**". It is therefore necessary to identify the dose metrics or the quantity that is closely related to the effect of concern, i.e., induced electric field and specific absorption rate (SAR) for EMF exposure.

In this presentation, **general methodology** for EMF dosimetry will be presented at first. As the most important background of the methodology, the **electrical properties** of the biological tissues and organs are introduced. Then **EMF coupling** between a biological body and an EM source will be discussed.

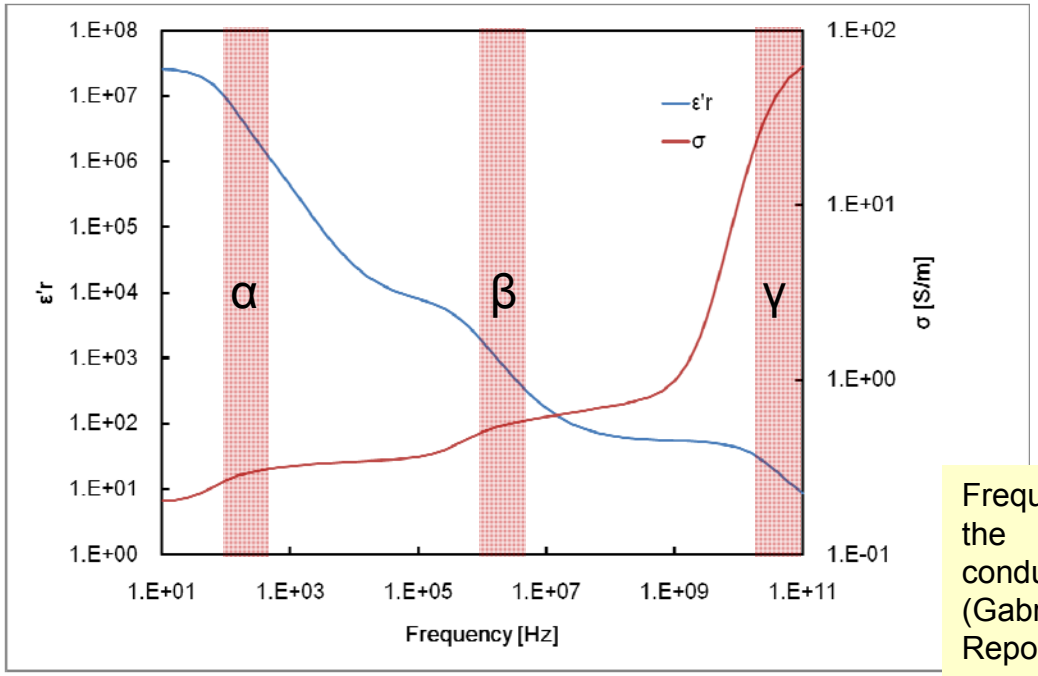
In the second part of this presentation, some topics of EMF dosimetry in **RF region** will be summarized. Especially issues about **children and fetuses** will be addressed.

Electrical properties of biological tissues and organs

Biological tissues and organs are **lossy dielectric**, which is characterized with the relative permittivity (ε'_r) and conductivity (σ) or with the relative complex permittivity ($\varepsilon'_r - j\,\varepsilon''_r$).

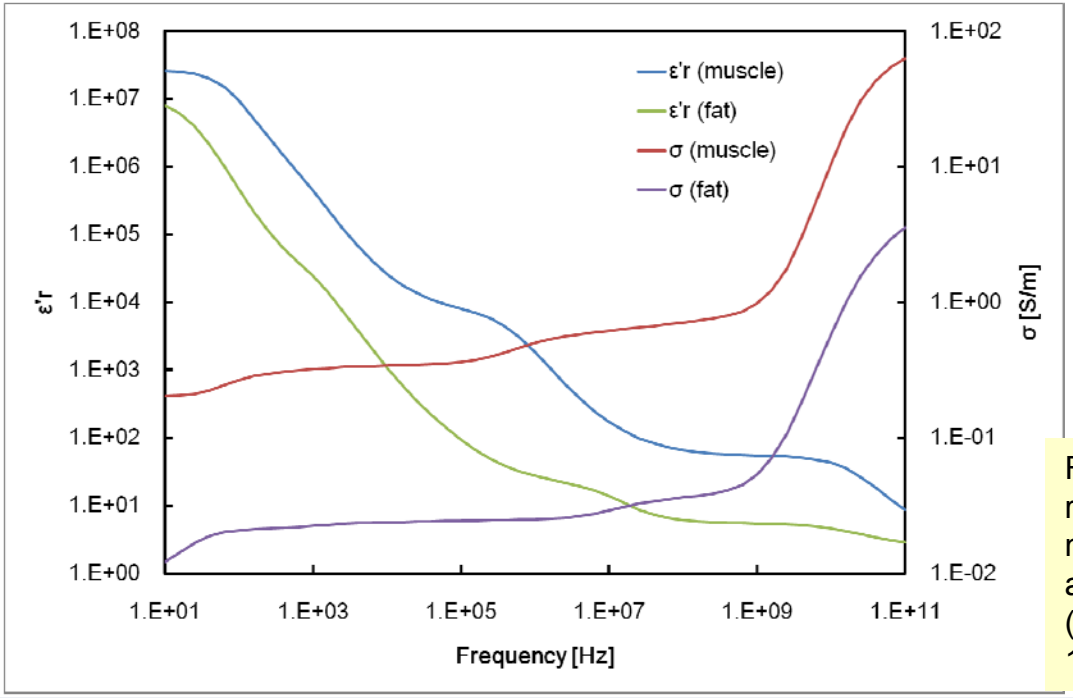


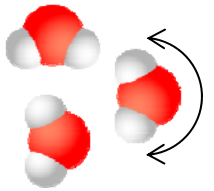
Frequency characteristics of the relative permittivity and conductivity of muscle tissue (Gabriel, et al., Brooks AFB Report, 1996).

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

Electrical properties of biological tissues and organs

Electrical properties of biological tissues and organs are significantly variable, which can be 100 times.





Rotation of water molecules† causes γ dispersion.

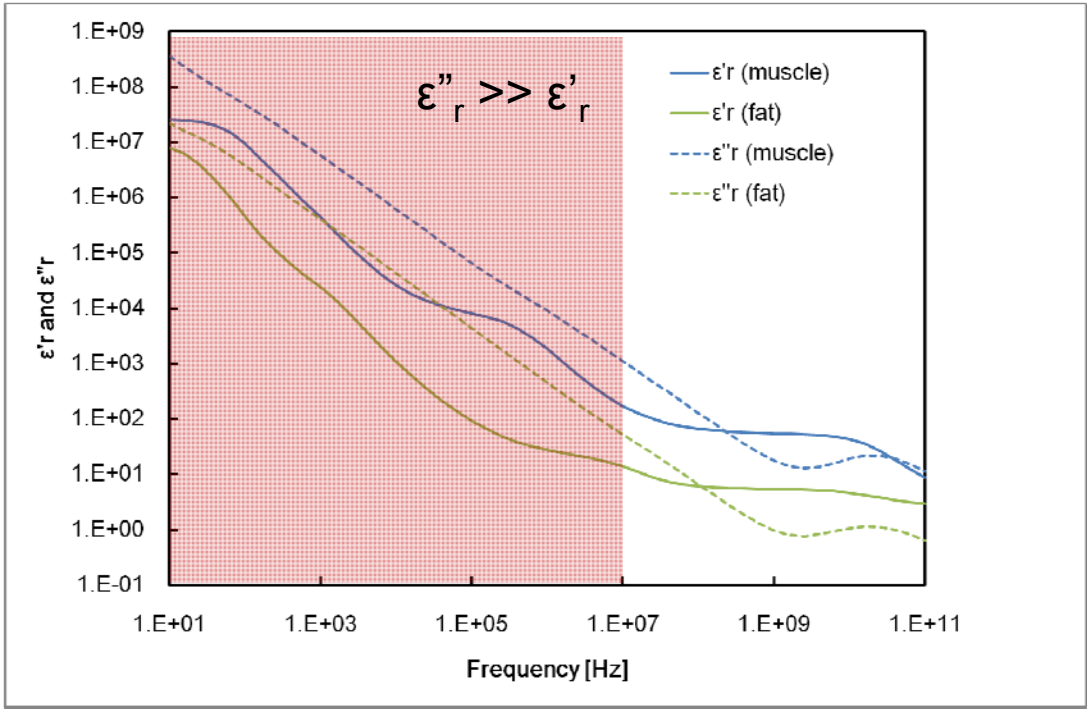
Frequency characteristics of the relative permittivity and conductivity of muscle as a high-water-content tissue and fat as a low-water-content one (Gabriel, et al., Brooks AFB Report, 1996).

Electrical properties, especially conductivity, strongly depend on the **water-content ratio** of the biological tissues or organs.

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

Electrical properties of biological tissues and organs

At lower frequencies (~10 MHz), the biological tissues and organs generally act as a **good conductor** ($\varepsilon''_r >> \varepsilon'_r$).



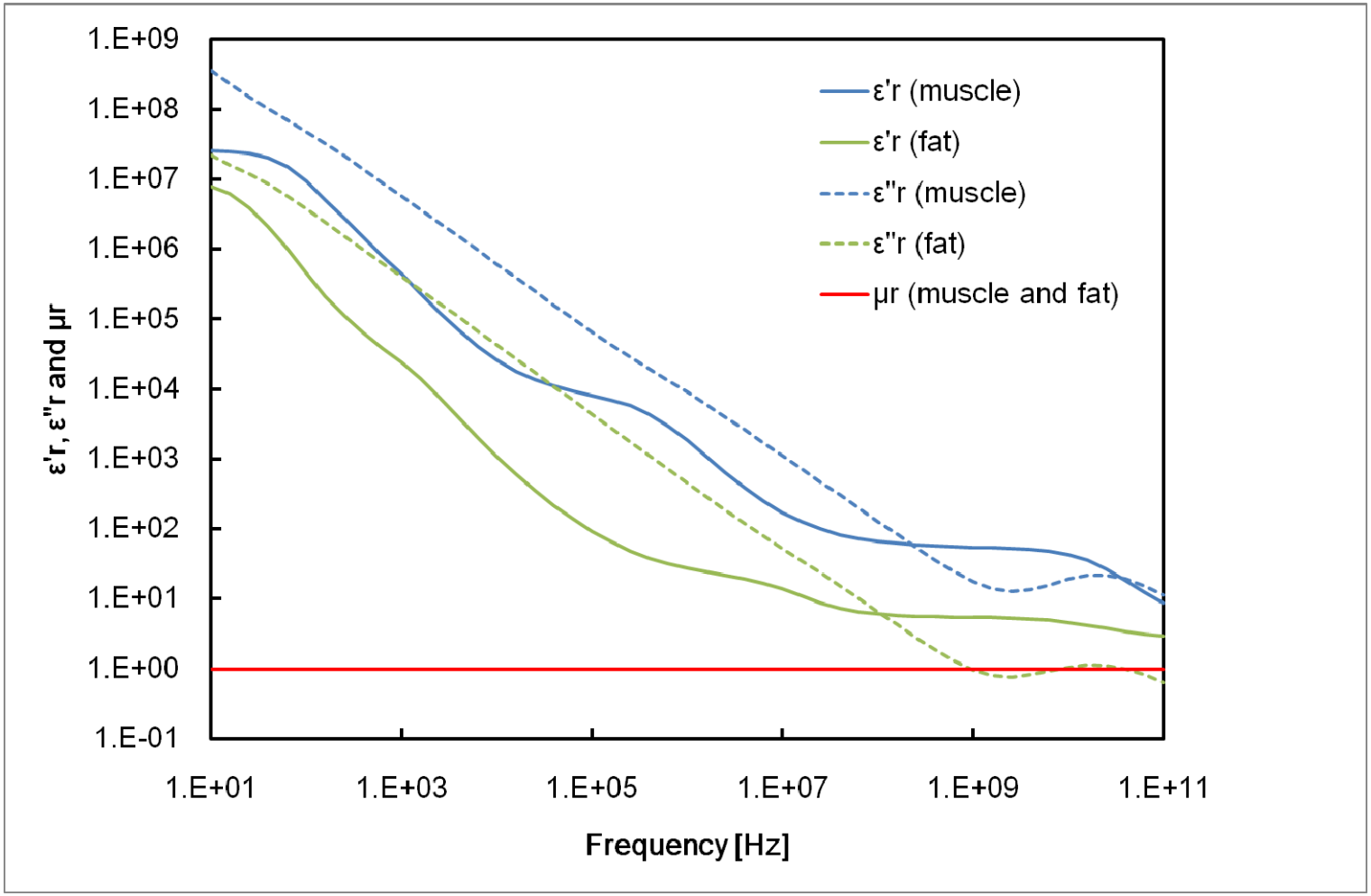
$$\varepsilon''_r = \sigma / (2\pi \cdot f \cdot \varepsilon_0)$$

$$\varepsilon_0 = 8.8542 \times 10^{-12} \quad [\mathrm{F/m}]$$

At lower frequencies, the biological tissues and organs are mainly characterized with **only conductivity** (σ or ε''_r) but not with the permittivity (ε'_r).

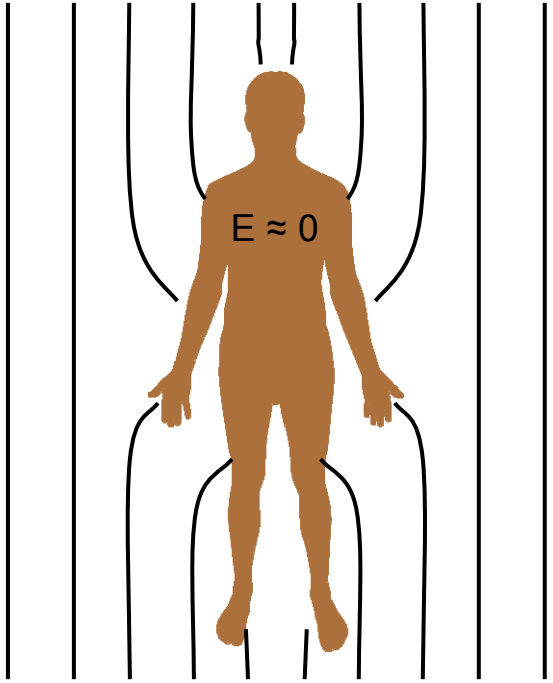
Electrical properties of biological tissues and organs

Biological tissues and organs have **no magnetism**, i.e., $\mu_r = 1$.



EMF coupling with biological bodies depnds on frequency and the body size

E-field coupling with biological bodies at DC and ELF is the same as that with **metal objects.**

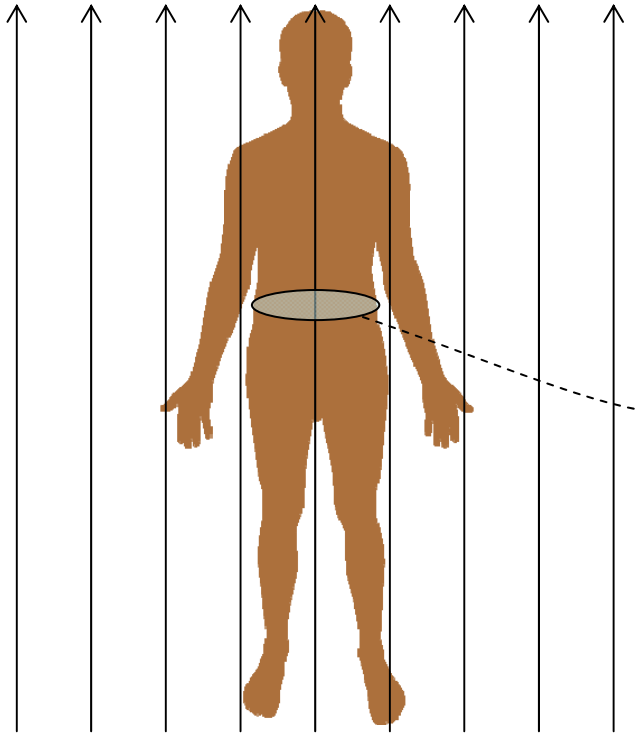


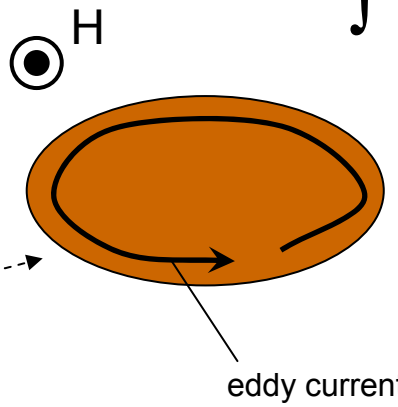
The charge or current flow appears on the surface of the body while **no E-field or current flow exists inside of the body**.

Picture of the human body is modified from http://commons.wikimedia.org/wiki/File:Human_body_silhouette.svg.

EMF coupling with biological bodies depnds on frequency and the body size

H-field coupling with biological bodies at DC and ELF is caused by the **electromagnetic induction** governed with Maxell-Faraday equation while **Lorentz force** caused in a moving conducting object is generally insignificant.





$$\oint \mathbf{E} \bullet dl = -\int_S \mu \frac{\partial \mathbf{H}}{\partial t} \bullet d\mathbf{s}$$

Faraday's law of induction

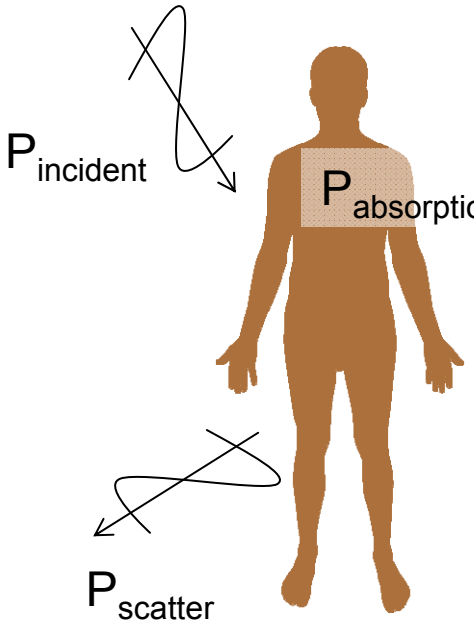
$$\mathbf{F} = qv \times \mu\mathbf{H}$$

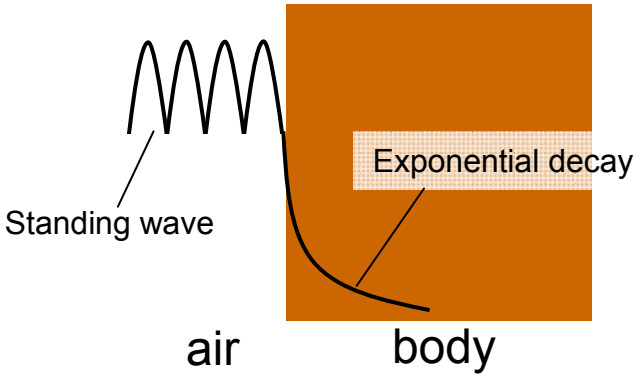
Lorentz force eq.

Induced current or eddy current generally becomes **maximum around surface region**.

EMF coupling with biological bodies depnds on frequency and the body size

EMF coupling with biological bodies at higher frequencies includes **scattering** from the body and **absorption** by the body.





$$\mathbf{E} = E_{surface} \cdot \mathrm{e}^{-\frac{x}{\delta}}$$

Skin depth effect. δ is skin depth.

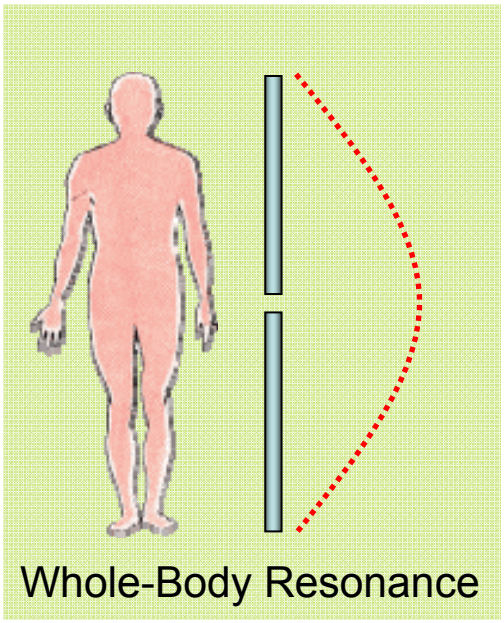
$$\mathrm{SAR} = \frac{\sigma |\mathbf{E}|^2}{\rho} \quad [\mathrm{W/kg}]$$

Specific absorption rate. ρ is the density [kg/m^3].

Internal field strength **decays exponentially** because of the skin depth effect. EMF absorption of the body is evaluated with the specific absorption rate (SAR).

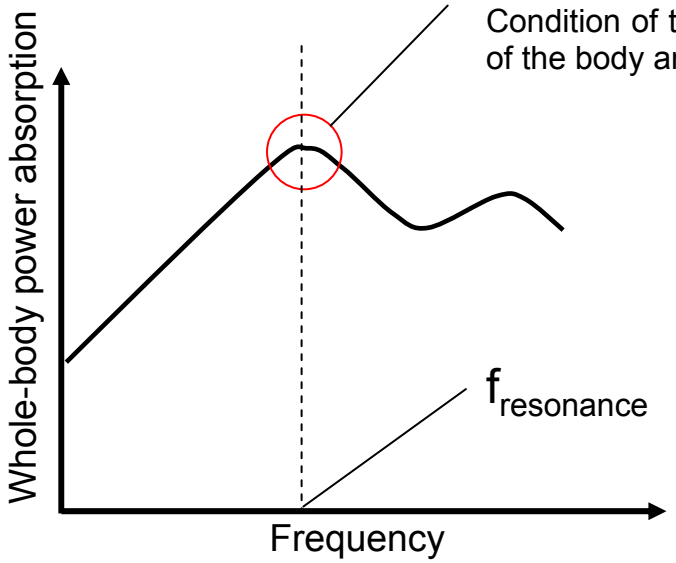
EMF coupling with biological bodies depnds on frequency and the body size

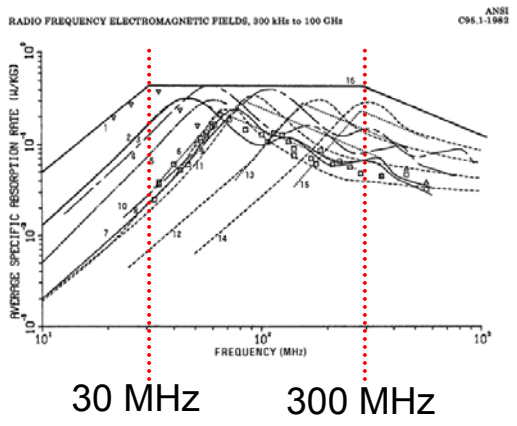
When the biological body length is comparable with the wavelength of EMF and parallel with the direction of the E-field, the body acts as a resonant antenna, known as **the whole-body resonance**.



$$L/\lambda_{resonance} = Lf_{resonance}/c_0 \approx 0.4$$

Condition of the whole-body resonance. *L* is the tall length of the body and c_0 is the speed of light in free space.

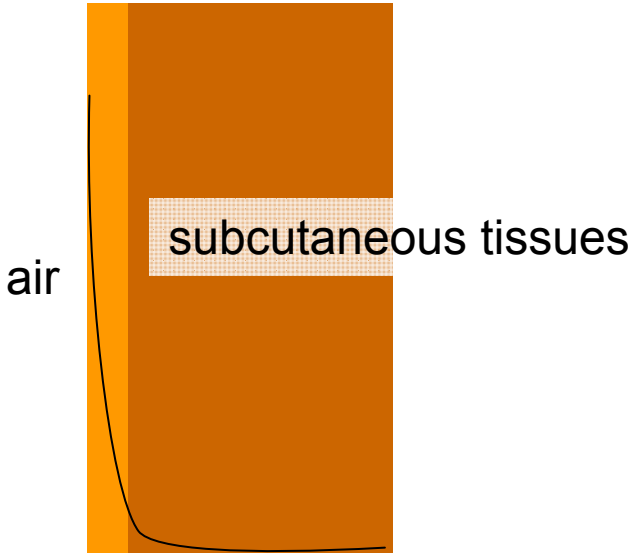


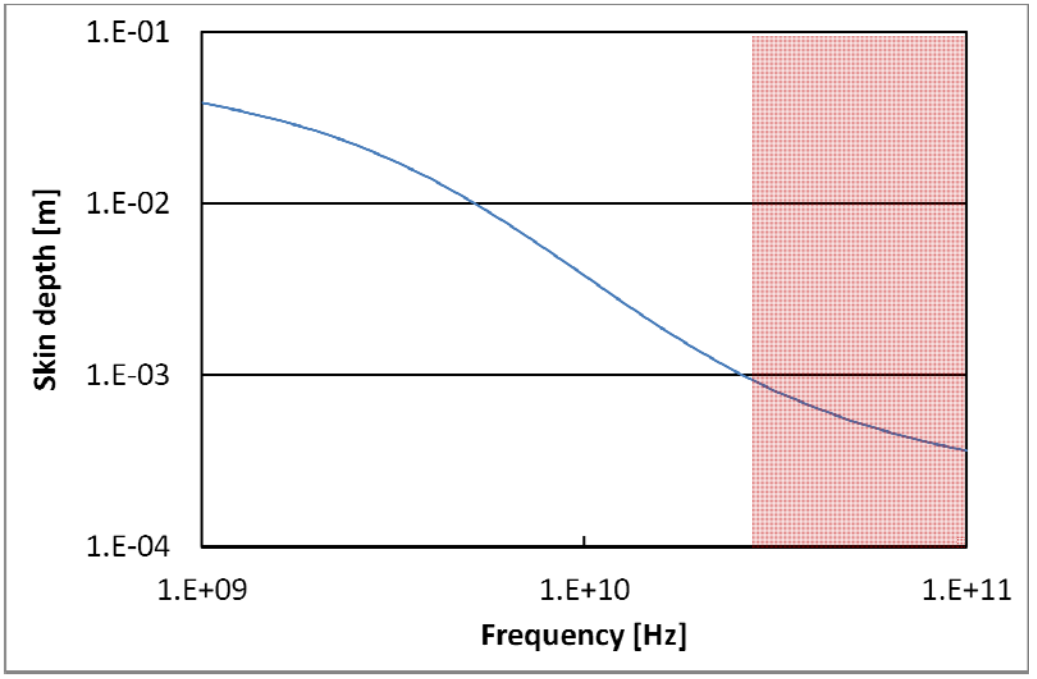


In the case of the whole-body resonance, the biological body effectively aborbes EMF power. The whole-body resonance appears **from 30 MHz to 300 MHz, depnding on the tall length of the human body.**

EMF coupling with biological bodies

At frequencies higher than the whole-body or partial-body resonance, EMF coupling with biological bodies mainly occurs **only within the surface region** because the skin depth is very short compared with the body.





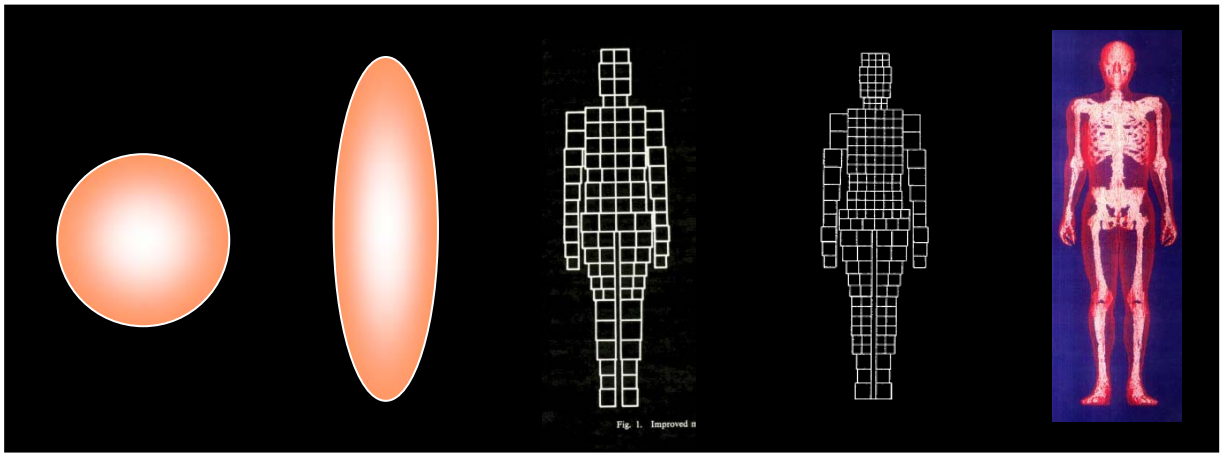
In millimeter-wave (MMW) frequency region (30 GHz ~), most power absorption is limited within **1 mm or less from the skin surface**.

Theoretical methods of EMF dosimetry

Analytical methods with simple human models have been used to evaluate general characteristics. With recent advancement of computer performance, numerical simulation with **realistic voxel human models** are widely used to evaluate detailed/specific characteristics.

Primitive — Human Model — Realistic

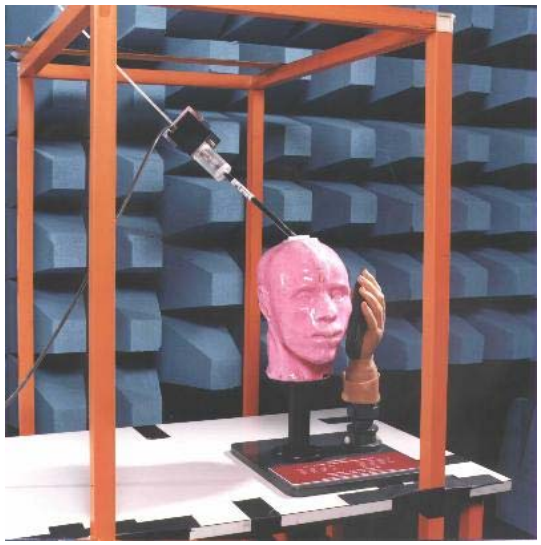
Low — Calculation Cost — High



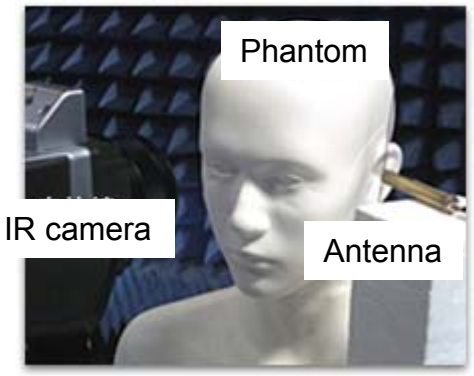
Sphere	Spheroid	180 blocks	626 blocks	9M voxels
Mie Theory	EBCM	MoM	CG-FFT/MoM	FDTD
’60~’70	’70~’80	’70~’80	’80~’90	’90~

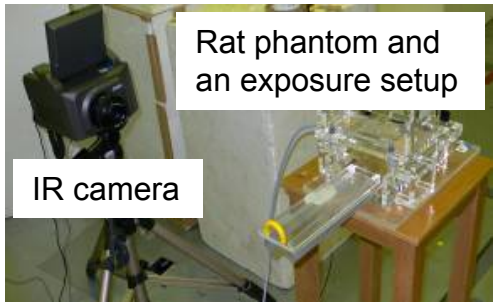
Experimental methods of EMF dosimetry

Experimental methods with simple, generally homogeneous, phantoms have also been used to evaluate EMF coupling with **an actual EMF source** and a human body while it is difficult to model the EMF source including complex electric circuits in the numerical simulation. In order to validate EMF dosimetry evaluation, it is recommended to compare between the theoretical method and the experimental one.



SAR measurement with an **E-field probe** in a human head phantom (left; NPL, right; SPEAG Inc.,).

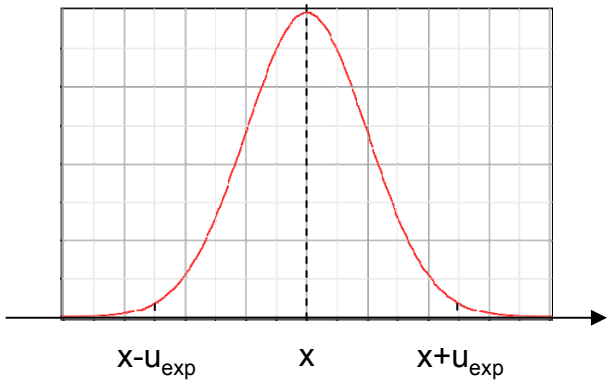




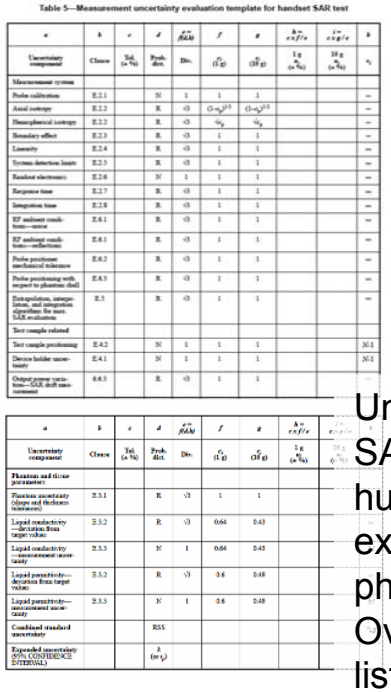
SAR measurement with an **IR camera** which measures surface temperature elevation due to EM power absorption (Left; Chiba Univ., right; NICT).

Uncertainty of EMF 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.



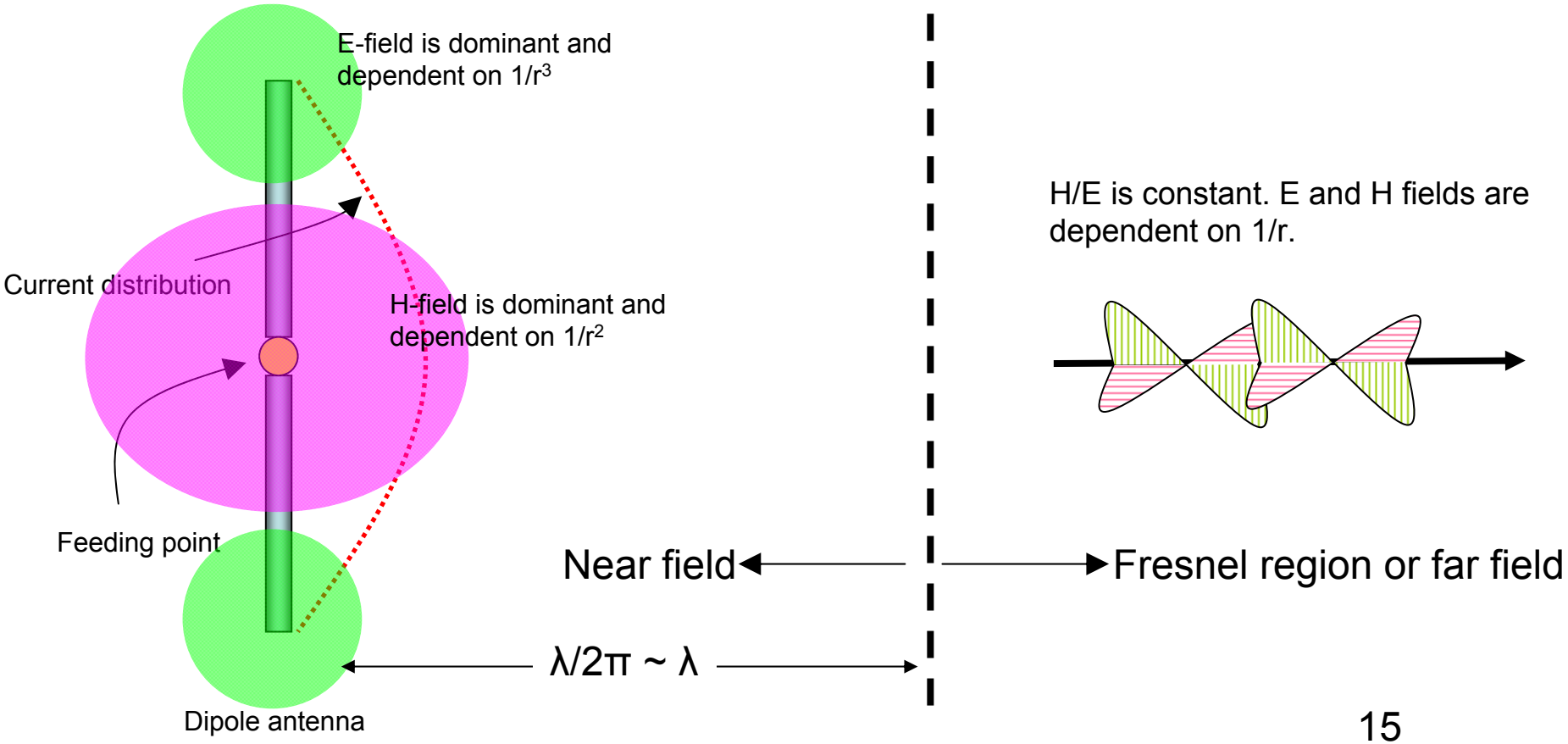
Measured or calculated value exists from $x-u_{exp}$ to $x+u_{exp}$ with 95-% of the probability, where u_{exp} is the expanded uncertainty.



Uncertainty budget for SAR measurement of a human head phantom exposed to a cellular phone (IEC 62209-1). Over 20 factors are listed in the budget.

RF Dosimetry --- Near field and far field

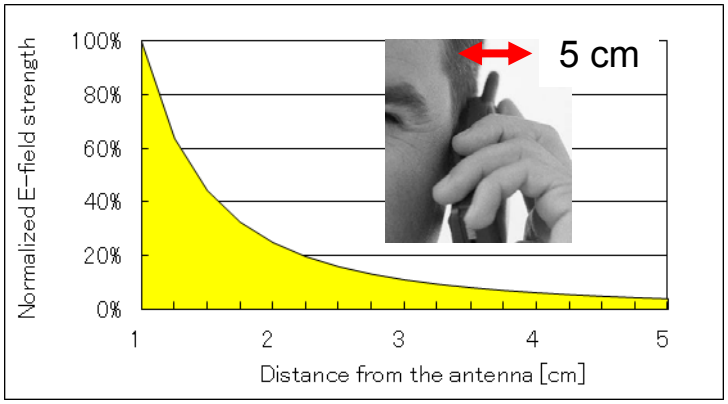
Characteristics of RF EMF radiated from an antenna greatly changes depending on the distance and direction from the antenna. Generally well-known EMF is far field which appears far from the antenna while near field shows **very complex behavior**.

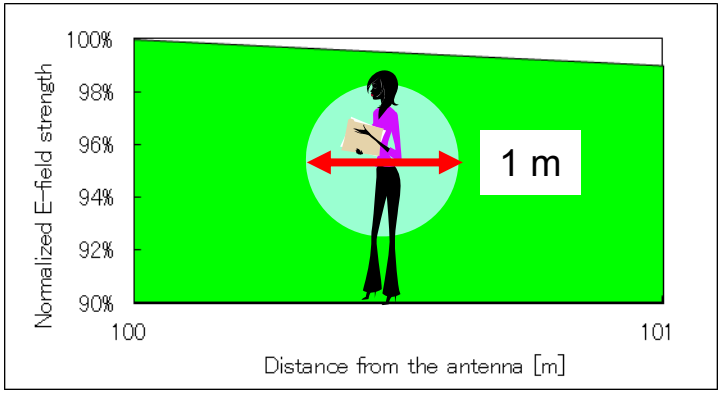


RF Dosimetry --- Human body in near field and far field

Spatial gradient of the incident EMF into a human body is considerably different between near-field and far-field. Near-field exposure causes **partial-body exposure** while far-field exposure does **whole-body exposure**.

Antenna of a cellular phone (900-MHz dipole antenna)

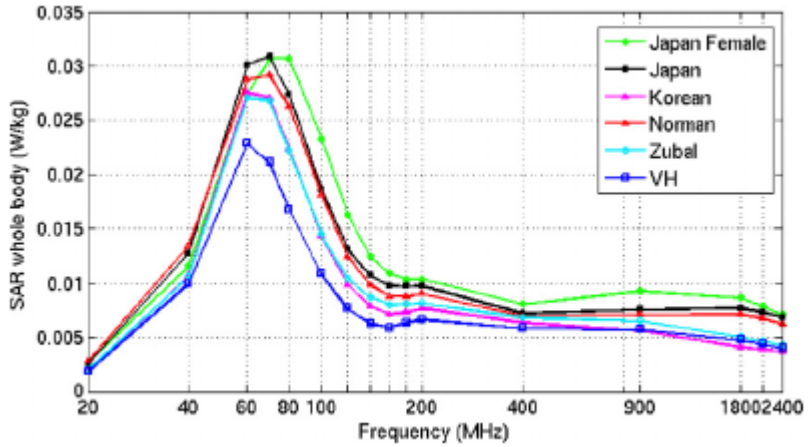




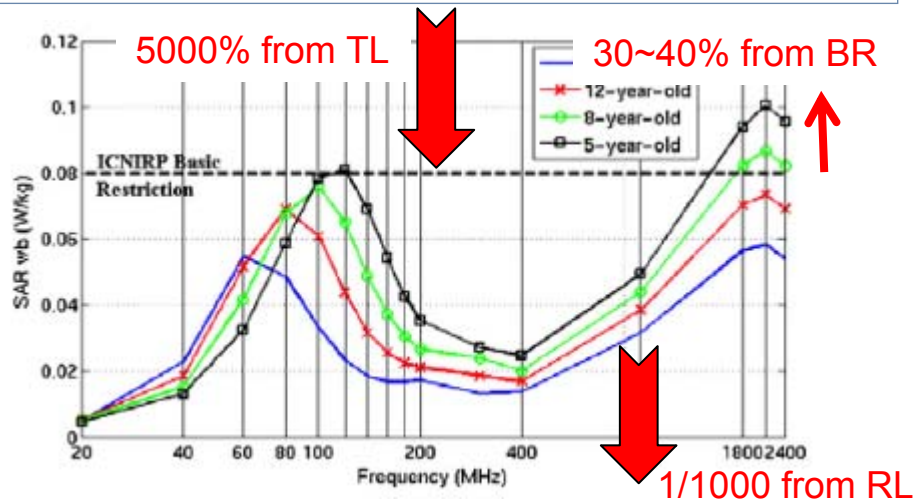
1 cm → 5 cm: EMF strength reduces by 96%. 100 m → 101 m: EMF strength changes only 1%.

RF Dosimetry --- Whole-body exposure

For whole-body exposure by far EMF sources such as base stations, **whole-body averaged SAR** is the most important dosimetry index. Recently, **30 % to 40 % increase** of whole-body averaged SAR in **children** compared with the basic restriction (BR), i.e., 0.08 W/kg, have been reported, which is still significantly smaller than the reduction factor considerd in the RF EMF exposure guidelines, i.e., 5000%. It is also noted that the EMF strength from a **base station** is typically **1/1000 or less** than the reference level (RL) of the ICNIRP guidelines.



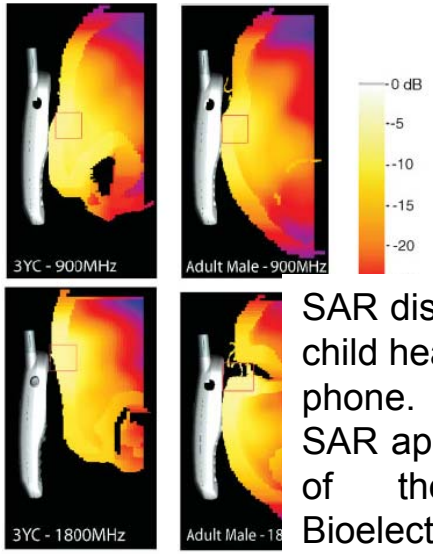
Frequency characteristics of WBA-SARs of various adult human models exposed to 1-mW/cm plane wave (far-field). (Conil, et. al., PMB 2008)



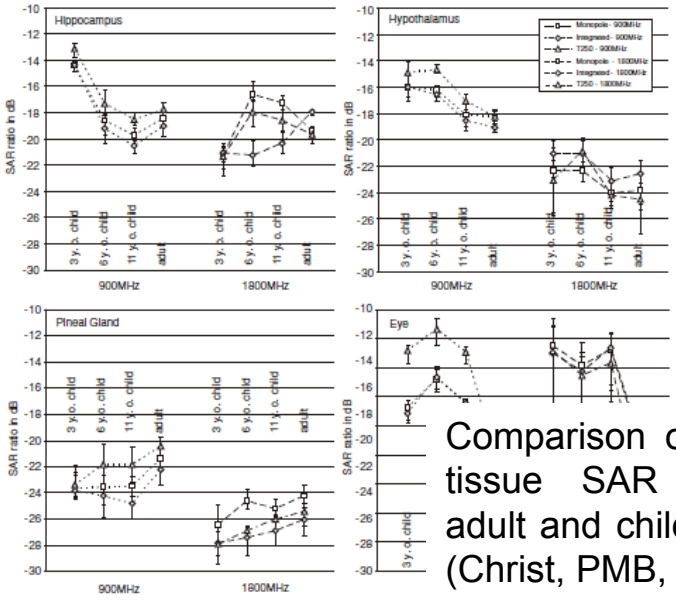
Frequency characteristics of WBA-SARs of various child human models exposed to plane wave of ICNIRP's reference level. (Conil, et. al., PMB 2008).

RF Dosimetry --- Partial-body exposure

For partial-body exposure by near-by EMF sources such as cellular phones, locally averaged SAR, e.g., **10-g tissue averaged SAR**, is the most important dosimetry index. The highest local SAR appears around the surface of the body. There is **no significant difference** in the highest local SAR between children and adults. Recently **significantly higher SAR (~10 dB)** in the brain and bone marrow in the skull of **children** has been reported because the distance from the antenna is shorter and the water-content ratios of those tissues are much higher for children than for adults.



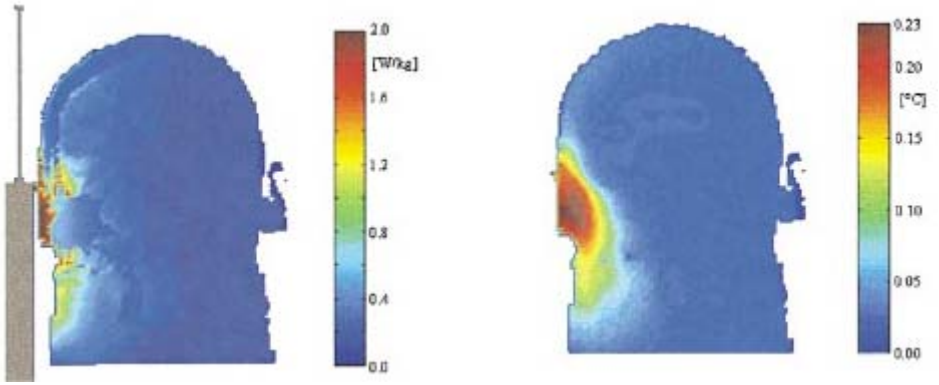
SAR distribution of adult and child heads holding a cellular phone. The highest local SAR appears on the surface of the body (Christ, Bioelectromag., 2005).



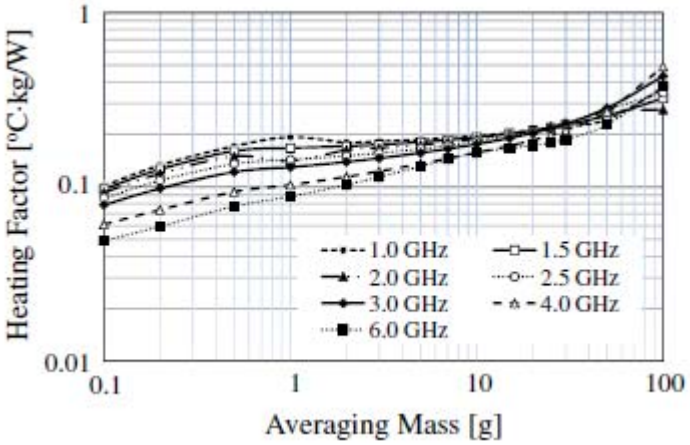
Comparison of internal tissue SAR between adult and child models. (Christ, PMB, 2010).

RF Dosimetry --- Temperature elevation

For RF dosimetry, not only SAR but also **temperature elevation** are important index because the safety guidelines are based on the thermal effects. Recently, detailed temperature simulation can be availlable. The temperature elevation by actual RF sources is **very low** compared with the threshold of the thermal effects, i.e., **1 degree Cercius**. The temperature calculation can provide **the relationship between SAR and temperature elevation** which is one of the most important rationale of the safety guidelines.



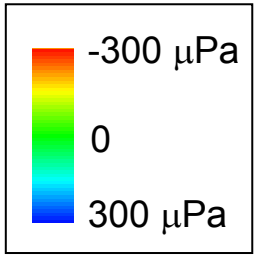
SAR and temperature distribution of a human head model holding a cellular phone (Bernardi, IEEE T-MTT, 2000).



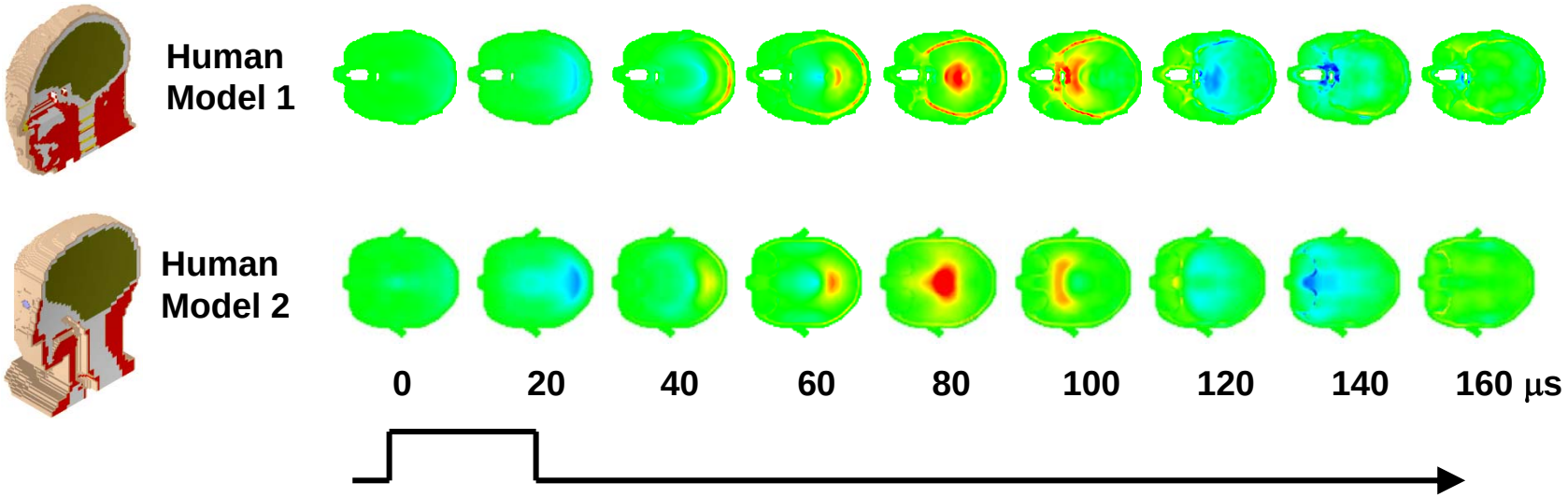
Heating factor (ΔT/SAR) as a function of the weight of local SAR. The variation of the heating factors from 1 to 6 GHz. is small around 10 g (Hirata, PMB, 2009).

RF Dosimetry --- MW hearing

In a human head exposed to **high-peak pulse wave**, MW hearing may occurs. In order to evaluate MW hearing, some studies have reported the elastic wave caused in the human head by transient heat energy of pulse wave. Temporal integral of SAR, i.e., **SA**, during the pulse width is a dominant factor for MW hearing.

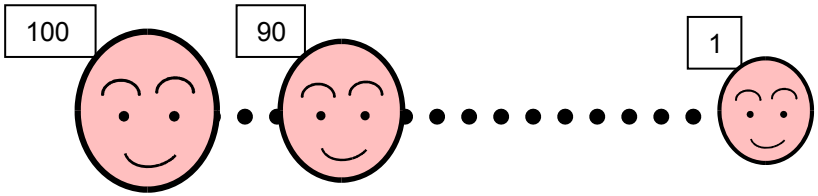


Numerical calculation of Elastic wave propagation in human head models (Prof. Taki (TMU)).



RF Dosimetry --- Compliance procedures

In order to evaluate the compliance with the safety guidelines of a RF source, **internationally standardized procedures** have been issued by ITU, IEC, and IEEE. These procedures are developed in consideration of **reproduceablity, simplicity, and reliablity** rather than accuracy.

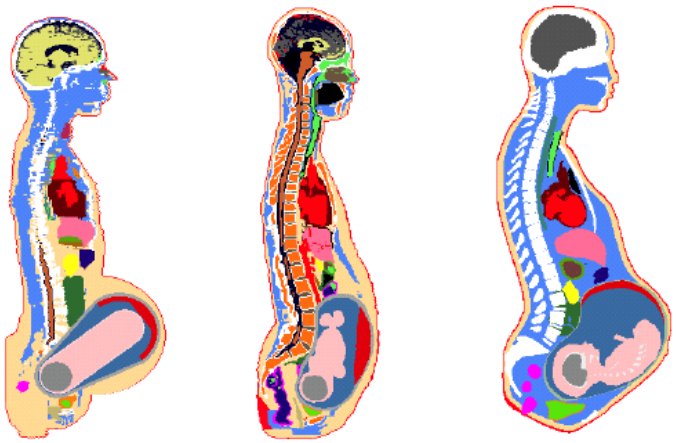


Standard head phantom , known as Specific Anthropomorphic Mannequin (SAM), is based on **90-percentile** dimension of adult males.

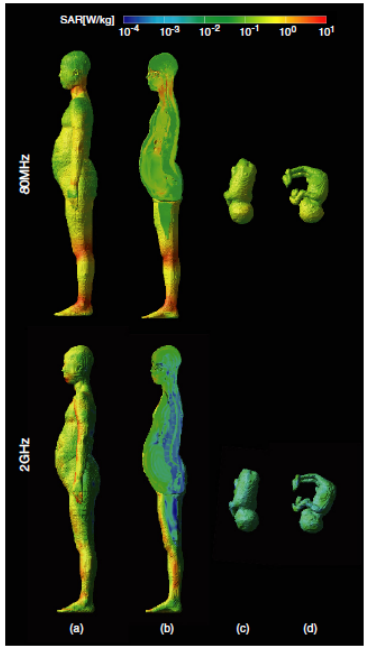
Calibration setup for a SAR probe.

RF Dosimetry --- Fetus

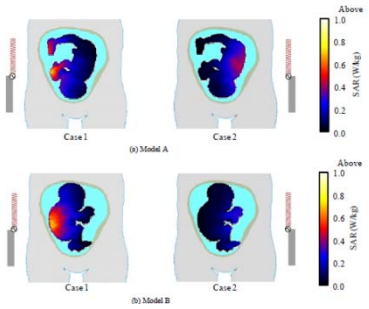
RF dosimetry of a fetus has recently become one of the important topics. The variety of the **location and posture of the fetus and placenta** makes difficulty in deducing general characteristics of fetus exposure. Active efforts to develop various pregnant woman models have been dedicated to overcome this problem.



Three pregnant woman models. The size and location of the fetus is variable. (Dimbylow, PMB, 2009).



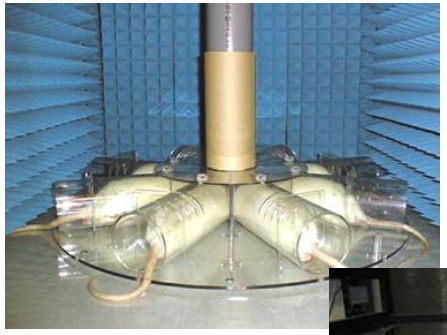
SAR distribution for far-field exposure at 900 MHz and 2 GHz. (Nagaoka, PMB, 2007).



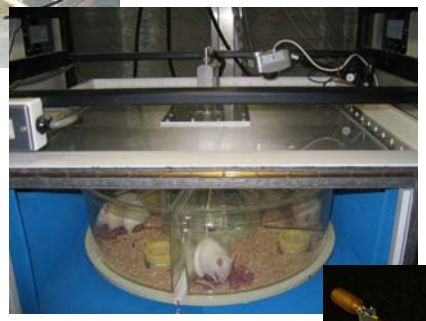
SAR distribution for near-field exposure in VHF band. (Akimoto, IEEE EMBS, 2008).

RF Dosimetry --- *In vitro, in vivo*, and human studies

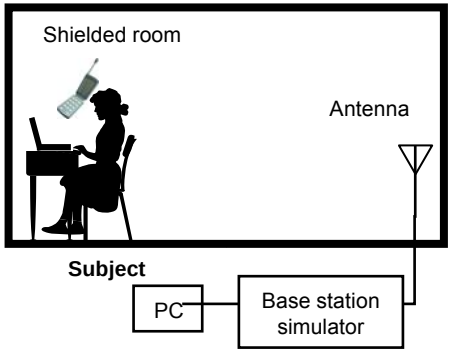
RF dosimetry is also necessary to develop the exposure setups for *in vitro, in vivo* and human studies. Evaluation of the **SAR and/or the temperature** elevation is especially important to **clarify/exclude thermal effects or non-thermal ones**.



In vivo exposure setups for head exposure (top), whole-body exposure (middle), and eye exposure (bottom) .



In vitro exposure setup with a temperature control system



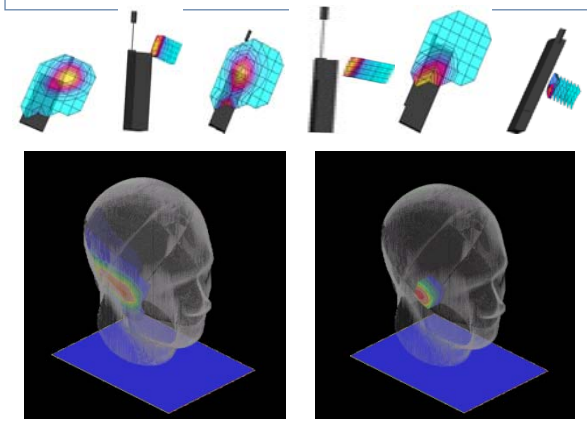
Human exposure system.

RF Dosimetry --- Epidemiological studies

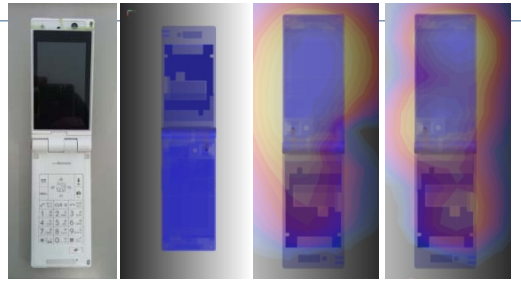
RF dosimetry for epidemiological studies has different aspects, i.e., we need to evaluate the **histrical exposure**, defined as below;

$$\text{Dose} = \sum_{i=1}^{N} \text{SAR}(t_i) \cdot t_i$$

In the first paper of *INTERPHONE* study on the glioma, SAR(t_i) is assumed as a **constant**, which means that only cumulative time of cellular phone's call is considerd. More detailed analyses based on the SAR distributions of classified cellular phone groups have been reported. Software modified phones (SMP) have also been used for validation of the answer to the questionair about histrical use of a cellular phone.



Categorization of SAR distribution based on the specification of cellular phones.



Measurement of SAR distribution of actual phones using a fast SAR measurement system.

Conclusion

General methodology of EMF dosimetry was presented at first.

The **electrical properties** of the biological tissues and organs significantly changes with frequency and water-content ratio. The **EMF coupling** between a biological body and an EM source is dependent on the frequency and the size of the body.

In the second part of this presentation, some topics of RF dosimetry following the comparison between near-field and far-field were summarized.

Recent studies with anatomical human models have reported that higher SAR can appear in a **child** than in an adult. SAR in a **fetus** is generally lower although relatively higher SAR can appear if the distance between the source and the fetus is short. **Temperature elevation** will be a key index to discuss the safety guidelines in RF region.

Thank you!