UNIVERSITÀ DI PISA

Electromagnetic Radiations and Biological Interactions

"Laurea Magistrale" in Biomedical Engineering
First semester (6 credits), academic year 2011/12

Prof. Paolo Nepa
p.nepa@iet.unipi.it

Experimental Dosimetry

Edited by Dr. Anda Guraliuc

MRL Microwave & Radiation Laboratory

Lecture Content

- **Body Phantom**
- **SAR measurement methods**
  - Measurements using miniature electric probes
  - Measurements using temperature sensors
  - Absorbed power measurements
- **Physical scaling**

Introduction

➢ Dosimetry quantifies the interaction of RF fields with biological tissues and bodies. It plays an important role in risk evaluation of human exposure to RF fields, as well as in the design of RF/microwave biomedical systems.

➢ Experimental dosimetry involves direct measurements:

- average SAR measurements and SAR distribution in animals
- average SAR measurements and SAR distribution in artificial models (phantoms) of animals/human body.

➢ Experimental dosimetry requires the development of:

- EM exposure systems easily controlled
- SAR measurement systems: field probes, thermometers

➢ Experimental dosimetry also allows to:

- compare experiments of different laboratories and different exposure systems
- verify theoretical (analytical and numerical) models

Body phantoms

- Because SAR measurements on animals provide difficulties and uncertainties, some synthetic materials have been developed to simulate biological tissues, called *phantoms* with dielectric properties similar to those of the tissue to be simulated (biological tissue equivalent).

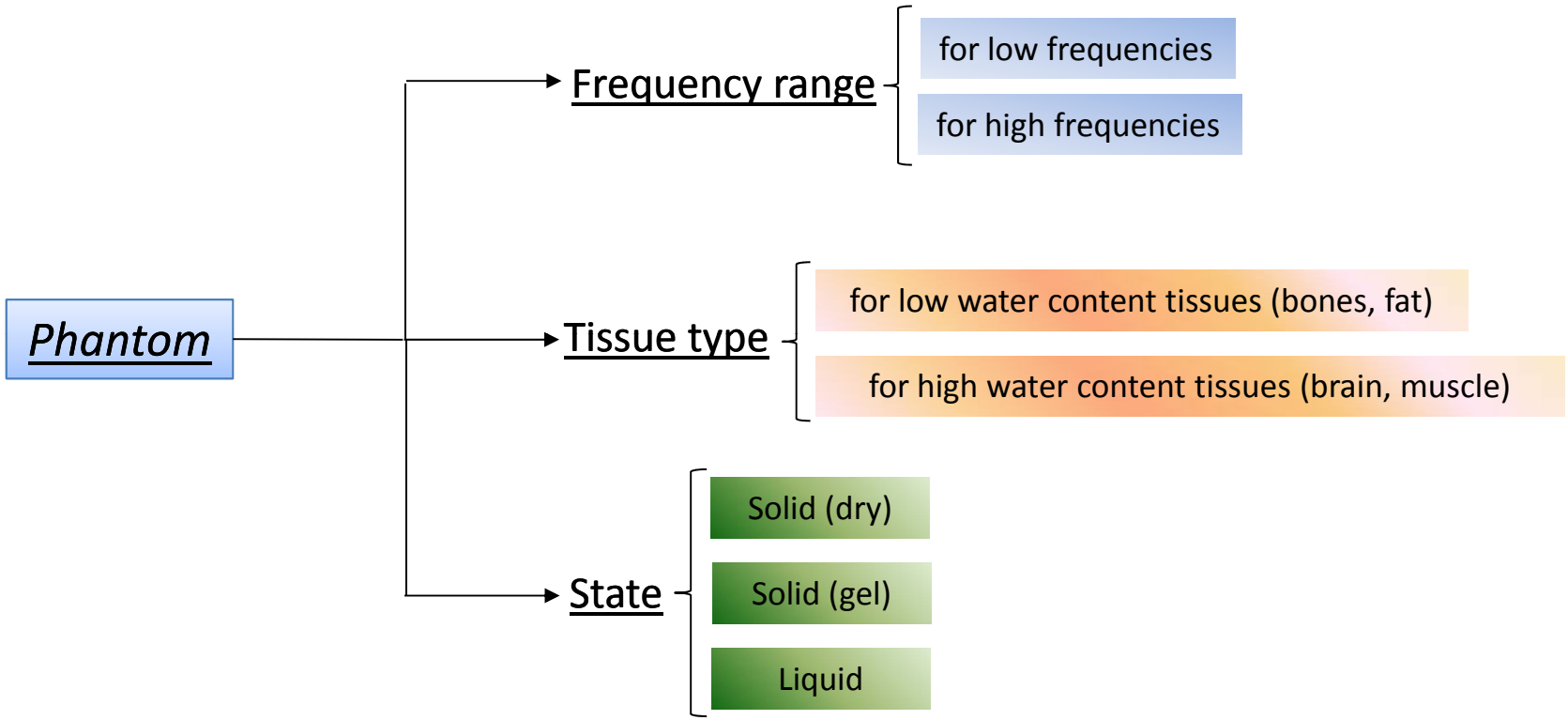
- Its aim is to explore the interaction between the human tissue and the electromagnetic fields.

- Have been intensively used in medical research on the effects of EM radiation on health, but also to develop methods for medical diagnosis and treatment like MRI scans, hyperthermia.

- They are essential tool for designing and testing communication devices used close to the body (wearable wireless devices). They are valuable tools in the study of radiowave propagation around and inside the body.; indeed, their use can provide a stable, controllable propagation environment, which can not be easily realized with human subjects.

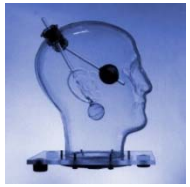
- Safety guidelines: ICNIRP and IEEE established acceptable SAR levels that can be easily measured using methods that involves standard phantoms.

Phantom classification criteria



Liquid phantom

Liquid



- Used in *SAR* studies by measuring the electric field inside the phantom using a small probe
- it consists of a container with the shape of the head or the entire body; for frequencies from 0.8 to 3GHz, the container is made by a thin shell (thickness 2±0.2mm) made of fiberglass with low relative permittivity (less than 5) and conductivity (loss tangent less than 0.05)
- the shell presents a hole to allow the probe insertion
- the container is filled with a liquid that has electrical characteristics similar to those of human tissues (average permittivity): the solution is required to achieve a permittivity equal to 2/3 of that of the muscle (estimated average permittivity of the human body)
- at low frequencies the liquid contains sugar and at high frequencies diacetin di-ethylene glicol butyl ether (DGBE), to adjust the permittivity; the salt (NaCl) is used to adjust the conductivity.
- it allows the record of detailed distribution of the fields inside the phantom (by using robot-controlled probes)

- advantage: cheap, simple to be realized and do not need special procedures or equipments
- disadvantage:
  - it does not allow SAR dose measurement close the body surface
  - it does not represent accurately the human body (the internal structure is a homogeneous medium)
  - the container electrical characteristics should be taken into account
  - the limited range of frequencies over which the liquid can have the required dielectric properties

[P.S. Hall, Y. Hao, "Antennas and propagation for body-centric communication", Artech House, 2006.]

Solid-Gel phantoms

Solid (gel)

- it uses a solidifying agent which makes the material jelly-like capable of self-shaping, eliminating in this way the outer shell used in liquid phantoms
- using solidifying agents like agar and TX-151 (a polysaccharide material), it results phantoms suitable only for simulating high-water content materials (muscle, brain). Combined with polyethylene powder (PEP) (control the permittivity), NaCl (control the conductivity) it is possible to adjust the electrical characteristic over a wide frequency range
- another gel material polyacrylamide is capable of simulating both high- and low-water content materials, depending on the liquid solvent used in its fabrication. The material is transparent and can be used in a wide frequency range, up to 5.8GHz

• advantages:

- can be remodeled and are easy to produce
- easy adjustment of dielectric constant, can be in multiple layers
- does not need a container or shell
- cheap and easily obtained ingredients

•disadvantage:

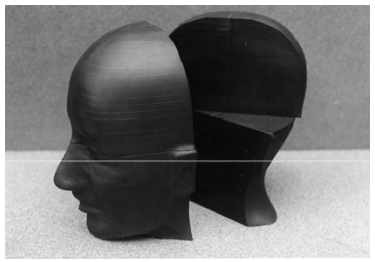
- it degrade over time due to the loss of water and/or the growth of fungi
- life time expectancy of about one month with wrapping
- phantoms based on agar and TX-151 are suitable only for high water content materials
- phantoms based on polyacrylamide need special care because of its toxicity. The useful frequency range of this phantom is narrower than that of the agar and TX-151 phantom

[P.S. Hall, Y. Hao, "Antennas and propagation for body-centric communication", Artech House, 2006.]

Solid-Dry phantoms

Solid (dry)

- is usually used for body surface SAR measurements
- contains ceramic and graphite powder, carbon powder with silicone rubber and conductive plastic with black carbon



- advantages:
  - have excellent mechanical and dielectric properties that do not degrade over long time, since they do not contain water
  - allows the measurement of SAR on the surface of the body (performed by thermography)
  - it can represent the inhomogeneous structure of the human body (preserve the internal structure of the body inside the phantom for a long period of time)

- disadvantage: advanced equipment is required and special production conditions: high temperature (180°C) and high pressure.

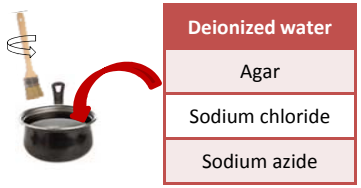
[P.S. Hall, Y. Hao, "Antennas and propagation for body-centric communication", Artech House, 2006.]

How to make a phantom

(1) measure the mass of each ingredient

Deionized water
Agar
Sodium chloride
Sodium azide (NaN3)
TX-151
Polyethylene powder (PEP)

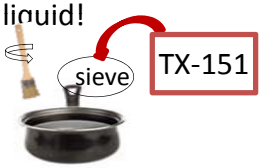
(2) add sodium chloride (to control conductivity), sodium azide (is a preservative) and agar in the pot filled with deionized water.



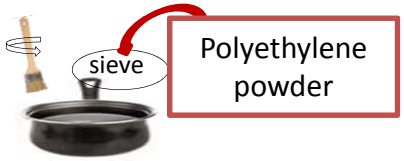
(3) heat the compound liquid

(4) stop heating when the symptom of boiling appears; small bubbles boil up. Note that the agar doesn't solidify if heating is insufficient

(5) mix TX-151 (to increase viscosity) through the sieve in the liquid little by little, and stir carefully so that air should not be mixed in. Do not beat the liquid!



(6) mix PEP through the sieve in the liquid little by little, and stir carefully as mixing TX-151 in.



(7) pour the liquid into the mould.

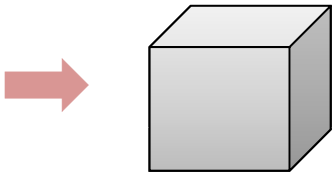
(8) put a sheet of plastic film on the mould after the liquid has been poured in, so that the phantom should not dry up.

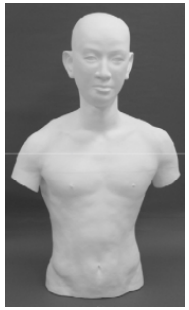
(9) cool the liquid approximately over a night at the room temperature.

(10) take out the phantom from the mould after it has hardened

(11) Cut off the top and bottom of the phantom for several cm, because the surface is usually not smooth.

(12) wrap the phantom with plastic film to prevent from drying up. The completed phantom can be preserved at room temperature.



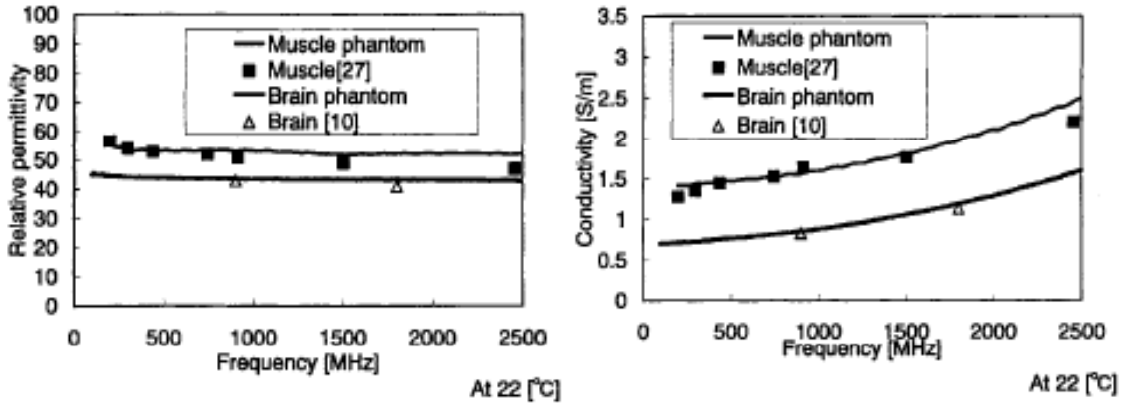


[P.S. Hall, Y. Hao, "Antennas and propagation for body-centric communication", Artech House, 2006.]

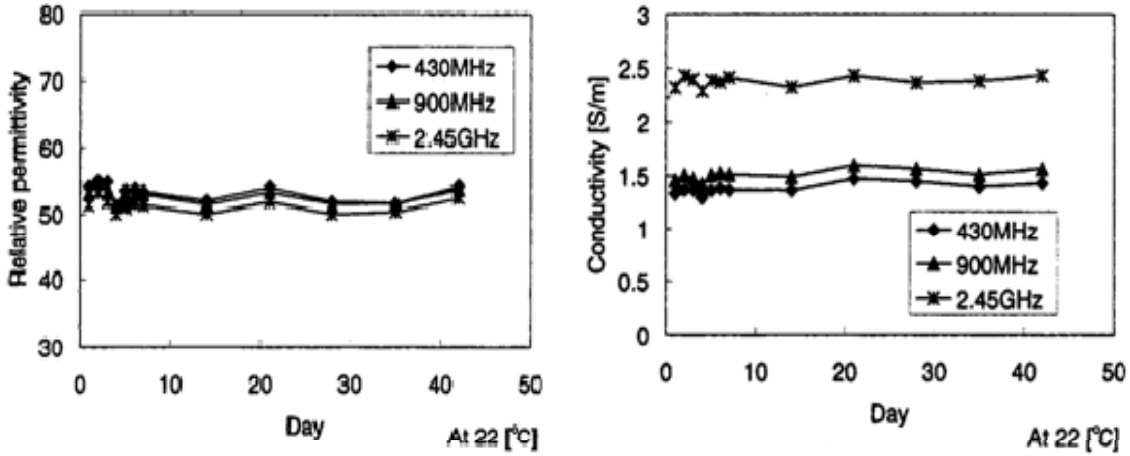
Adjustment of electrical characteristics (I)

Ingredients for biological tissue-equivalent phantoms

Ingredients	Muscle (g)	Brain (g)
Deionized water	3375	3375
Agar	104.6	104.6
Sodium chloride	37.6	21.5
Sodium azide (NaN_3)	2	2
TX-151	84.4	57.1
Polyethylene powder	337.5	548.1



Electrical properties of biological tissue-equivalent phantom



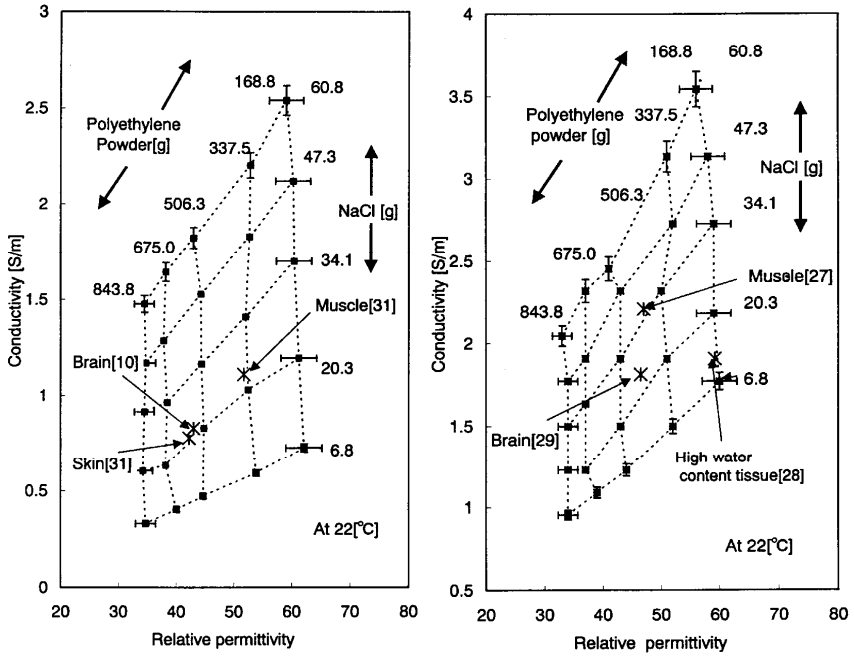
Time variation of the electrical properties of muscle-equivalent phantom

[K. Ito, K. Furuya, Y. Okano, L. Hamada, "Development and characteristics of a biological tissue-equivalent phantom for microwaves", Electronics and Communications, vol. 84, no. 4, pp. 67-77, December 2001.]

Adjustment of electrical characteristics (II)

- Electrical characteristics of the phantom need to be adjusted within a certain range.
- Phantoms are fabricated with varying amounts of polyethylene powder (PEP) and NaCl.
- For ease of mixing the PEP into agar, the TX-151 varies depending on the amount of PEP: $0.0001(PEP)^2 - 0.213(PEP) + 143.79[g]$

Phantom electrical properties adjustment: 900MHz and 2.45GHz



- The relative permittivity in mainly determined by the PEP
- The conductivity is affected by both PEP and NaCl
- The phantom composition with a desired characteristic can be determined first by deriving the amount of PEP needed for the relative permittivity, and then adjusting the conductivity with NaCl.

[K. Ito, K. Furuya, Y. Okano, L. Hamada, "Development and characteristics of a biological tissue-equivalent phantom for microwaves", Electronics and Communications, vol. 84, no. 4, pp. 67-77, December 2001.]

SAR measurement methods

Internal electric field

- Methods based on direct measurement of the internal electric field using miniature electric field probes (electric dipoles) to determine local SAR.

Temperature

- Methods based on registering the increased temperature using miniature temperature sensors (thermocouples, thermistors, fiber optic probes) or calorimeters or thermographic cameras – systems that use the relationship between the absorption of microwave energy and the temperature rise.

Absorbed power

- Methods based on absorbed power measurements in TEM cells or capacitors (whole-body SAR measurements).

Measurements using miniature electric field probes

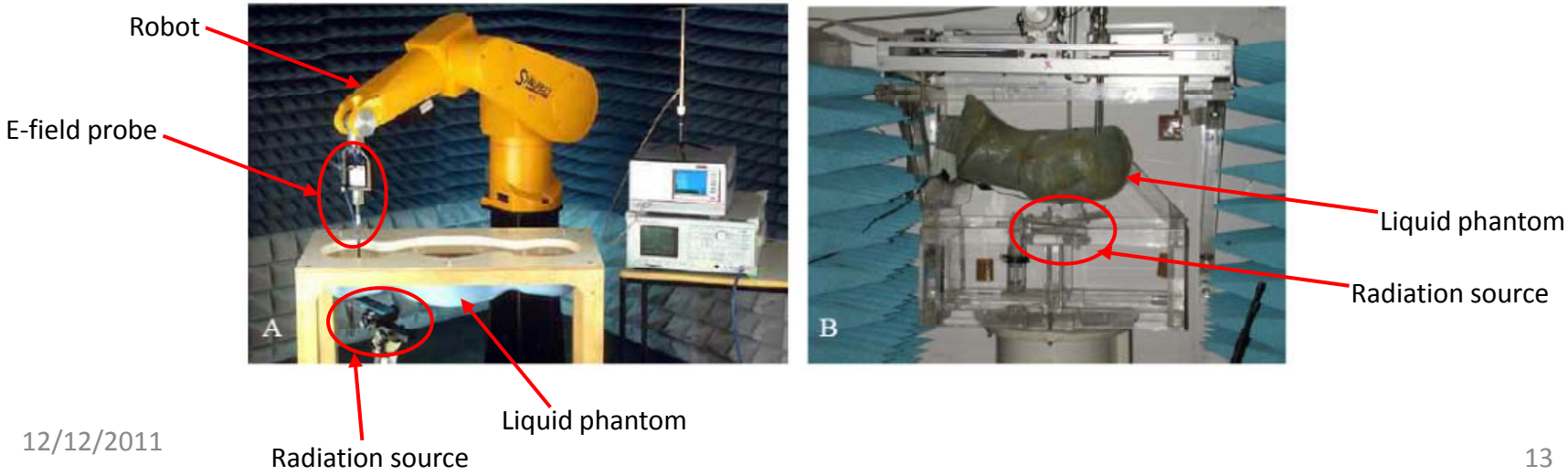
- SAR can be measured through electric field measurements:

$$SAR(\underline{r}) = \frac{\sigma(\underline{r})\left|\underline{E}(\underline{r})\right|^2}{2\rho(\underline{r})} \text{ [W / kg]}$$

- The method is based on the implantable E-field sensors (usually a small dipole) in a liquid phantom.
- A typical application is the maximum local SAR due to exposure by radiation sources (cellular phones) close to the body. The system consists in a small robot able to move the E-field sensors inside the phantom, ensuring good spatial resolution, accuracy and measurements repeatability.

• The minimum frequency accepted for these methods is determined by the maximum acceptable size of the electric field probes; the measurements sensitivity is low if dipole dimensions are small with respect to the wavelength. Probe size is determined by the spatial resolution to be obtained. Ex: if a spatial resolution of 1mm is desired, the maximum size of the field probe is 1mm; the maximum wavelength at which this sensor can be used is 1m (corresponding to 300MHz), if a probe greater than 1/1000 λ is required.

System for measurements of SAR induced in a phantom (ENEA Laboratories, Italy)



SAR measurements on different phantoms

Consider: two homogenous phantoms filled with brain equivalent tissue: cubic phantom (20x20x20cm^3) and anthropomorphous phantom.

Phantom Material	Amount (g)
Deionized water	3375
Agar	104.6
Sodium chloride	21.5
Sodium azide	2
TX-151	57.1
Polyethylene powder	548.1

Source	Cubic phantom		Anthropomorphous phantom
	SAR in 1g [W/kg]	SAR in 10g [W/kg]	SAR in 1g [W/kg]
DIPOLO 900MHz, 1W	8.98	5.75	4.9
GSM 900	0.47	0.31	0.38
DCS 1800	0.11	0.07	0.08

Cubic phantom represents the worst case, but it allows a repeatable position of the source and a precise evaluation of SAR in 10g.

G.A. Lovisolo, R. Pinto, D. Asta, S. Mancini, "Valutazione dell'efficacia degli auricolari nella riduzione dell'esposizione ai campi elettromagnetici emessi dai telefoni cellulari", Energia, ambiente e innovazione, 3, pp. 86-87, 2001.

SAR values for different cellular phones

- *SAR* measurements were performed using a standard compliance testing equipment. A phantom based upon the dimensions of a large adult male head, and filled with a liquid equivalent to the human head characteristics was used.
- The measurements were carried out by establishing a reference point in the phantom and then scanning a specified area in and around the phantom while the phone is operating at its maximum certified power level.

EU SAR (10g) limit: 2 W / kg

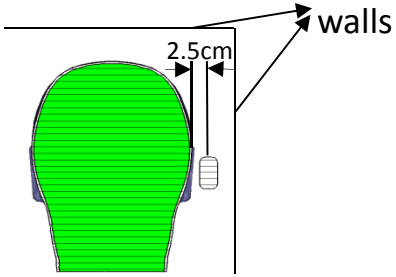
http://www.sarvalues.com/measuring-sar.html

Ten Lowest Radiating Cell Phones (EUROPE)		
Manufacture	**Model**	**SAR in 10g (W/kg)**
Samsung	F210	0.20
Nokia	6267	0.31
Emporia	Life	0.37
HTC	TYTN11	0.38
LG	KE970Shine	0.43
LG	KU970	0.43
Nokia	6290	0.47
Samsung	U600	0.48
Nokia	8800I	0.50
LG	KG130	0.52

Ten Highest Radiating Cell Phones (EUROPE)		
Manufacture	**Model**	**SAR in 10g (W/kg)**
SonyEricsson	T650	1.80
SonyEricsson	W880i	1.45
Nokia	E51	1.40
SonyEricsson	W950i	1.35
SonyEricsson	Z610i	1.32
SonyEricsson	K810i	1.31
SonyEricsson	W610i	1.31
SonyEricsson	W660i	1.27
SonyEricsson	K550i	1.25
LG+Nokia	KU250+N5700	1.24

SAR in users' head produced by phones in restricted areas

➢ In this experiment phones are used in restricted areas - cars, elevator- modeled through a vertical metallic wall placed at different distances behind the phone and in an opposite position of the user, or an horizontal wall placed above the head.



Case	SAR in 1g (W/kg)
Dipole ("Classic") 2.5cm	0.99
Microtac 2.5cm	1.08
Microtac 2.5cm with vertical wall at 4cm	1.71
Microtac 2.5cm with vertical wall at λ/4	1.58
Microtac 2.5cm with horizontal wall at 6cm	0.87

The peak value is located at the outer ear lobe, with no significant differences in the *SAR* distribution inside the head.

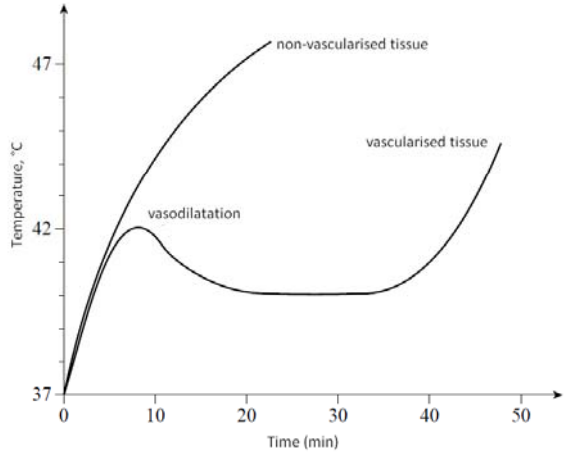
The peak value is lower than in the case of a vertical wall, with differences in *SAR* distribution: less at the top of the head, more at the bottom of the head.

✓ The peak SAR for typical used distances remained almost always below the limits (1.6 W / kg).
✓ When the source is placed at a small distance of the head and in the presence of a reflective vertical wall close to the user, peak *SAR* values may exceed the safety limits.
✓ The peak SAR is located at the external ear lobe.
✓ The eye, in these conditions, does not appear to be dangerously exposed.

A. Polichetti, E. Bortolin, R. Pinto, S. Mancini, G. A. Lovisolo, P. D'Atanasio, A. Zambotti, A. Moro, G. Antonucci, "Campi elettromagnetici emessi dai telefoni cellulari: verifica dell'efficacia schermante e protettiva di dispositivi commerciali", *Atti del Convegno Nazionale "Problemi e tecniche di misura degli agenti fisici in campo ambientale"*, Ivrea, Aprile 2001.

Bioheat equation (I)

- For temperature elevation above a certain level, the body reacts: it tries to eliminate the excess heat produced and keep its temperature constant. The heat transfer takes place within the body through **thermal conduction** through tissues, and mainly through **transport** by the organic fluid (blood).
- In the case of thermal conduction, the intensity of the thermal flux is proportional to the temperature difference between hot and cold spots and proportional to the thermal conductivity of the tissues in between.
- In the case of blood perfusion the regulation mechanism is governed by the local tissue temperature. If the temperature of a vascularized tissue exceeds 42°C, vasodilatation (thermophysiological response) amplifies the heat transfer from the overheated areas:



A. Hirata, M. Kojima, H. Kawai, Y. Yamashiro, S. Watanabe, H. Sasaki, O. Fujiwara, "Acute dosimetry and estimation threshold-inducing behavioral signs of thermal stress in rabbits at 2.45GHz microwave exposure", IEEE Trans. On Biomed. Eng., vol. 57, no. 5, May 2010.

Bioheat equation (II)

- Before exposure, the basal metabolism and heat transfer from the body to the air are balanced.

- After exposure, the temperature elevation inside the EM exposed tissues can be calculated with the bioheat equation:

$$c(\underline{r})\rho(\underline{r})\frac{\partial T(\underline{r},t)}{\partial t} = \nabla\cdot\left[K(\underline{r})\nabla T(\underline{r},t)\right] + \rho(\underline{r})SAR(\underline{r}) + A(\underline{r}) - B(\underline{r},t)\left[T(\underline{r},t) - T_B(t)\right]$$

$T(r,t)$- tissue temperature [°C]
$T_B(t)$- blood temperature [°C]
c - tissue specific heat [J/kg·°C]
K - tissue thermal conductivity [W/m·°C]
A - the basal metabolism per unit volume [W/m^3]
B - the term associated with blood flow [W/m^3·°C]

The solution of bioheat equation requires adequate boundary conditions on the air-tissue interface taking into account the radiative, convective and evaporative heat exchange:

$$-K(r)\nabla T(\underline{r},t)\cdot\underline{n} = -K(r)\frac{\partial T(r,t)}{\partial n} = h\left[T_s(r,t) - T_e(t)\right]$$

Heat transfer coefficient: $h = h_{rad} + h_{conv} + h_e$

surface temperature

air temperature

radiative heat loss

convective heat loss

evaporative heat loss

A. Hirata, M. Kojima, H. Kawai, Y. Yamashiro, S. Watanabe, H. Sasaki, O. Fujiwara, "Acute dosimetry and estimation threshold-inducing behavioral signs of thermal stress in rabbits at 2.45GHz microwave exposure", IEEE Trans. On Biomed. Eng., vol. 57, no. 5, May 2010.

Bioheat equation (III)

$$c(\underline{r})\rho(\underline{r})\frac{\partial T(\underline{r},t)}{\partial t} = \nabla\cdot\left[K(\underline{r})\nabla T(\underline{r},t)\right] + \rho(\underline{r})SAR(\underline{r}) + A(\underline{r}) - B(\underline{r},t)\left[T(\underline{r},t) - T_B(t)\right]$$

If the heating time is sufficiently short so that the effect of thermal conduction in the phantom can be neglected, the SAR can be derived:

$$SAR = c\frac{\partial T}{\partial t} \Leftrightarrow SAR = c\frac{\Delta T}{\Delta t}$$

Δt - time exposure
ΔT – Temperature elevation
c - tissue specific heat [J/kg·°C]

- *Bioheat equation is particularly effective in the shallow region of the body, where modeling the vasculature system is not required.*

- *The calculated temperature becomes unreliable in proportion to the distance from the body surface. In a 2.45GHz exposure system, the MW power absorption or heat source is concentrated around the surface, since the penetration depth is of few centimeters.*

[A. Hirata, M. Kojima, H. Kawai, Y. Yamashiro, S. Watanabe, H. Sasaki, O. Fujiwara, "Acute dosimetry and estimation threshold-inducing behavioral signs of thermal stress in rabbits at 2.45GHz microwave exposure", IEEE Trans. On Biomed. Eng., vol. 57, no. 5, May 2010.]

Measurements using miniature temperature sensors

➢ The temperature increase can be measured by thermistors, thermocouples or fiber optic thermometry, and then converted in SAR:

$$SAR = c\frac{\Delta T}{\Delta t}$$

Δt - time exposure
ΔT – Temperature elevation
c - tissue specific heat [J/kg·°C]

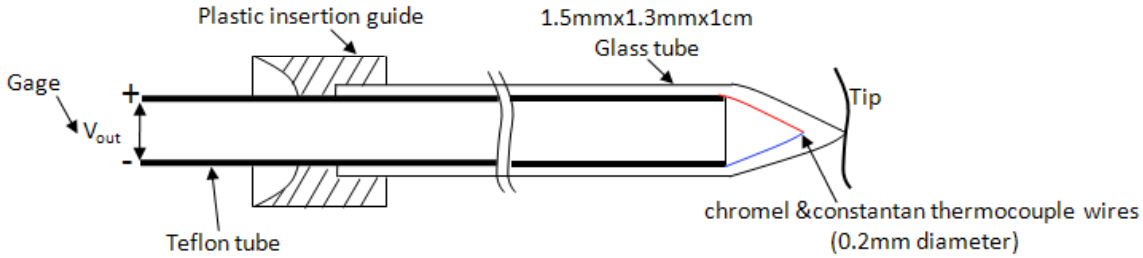
Limits

- the temperature sensor, left in the tissue, may introduce an alteration of the surrounding field and may help to raise the temperature
- temperature sensors often require considerable temperature variations, which makes them insensitive to low values of SAR.
- To increase temperature elevation high-field exposure are used to estimate SAR (SAR values at lower exposition values can be easily calculated analytically by assuming the absence of non-linear effects in the exposure field – internal field relationship)

Temperature probe: thermocouple

➢ The **Thermocouple** is a thermoelectric temperature sensor which consists of two dissimilar metallic wires, e.g. one chrome and one constantan, coupled at the probe tip (measurement junction) and extended to the gage junction.

➢ The temperature difference between the probe tip and the junction is detected by measuring the change in voltage (electromotive force, EMF). The absolute temperature reading can then be obtained by combining the information of the known reference temperature and the difference of temperature between probe tip and the reference.



✓The thermocouple is inserted into a glass or plastic pipette, which is implanted at the point where the absorption will be measured.

✓ The initial temperature will be recorded and the thermocouple is extracted.

✓ The body is irradiated with a high-power pulse (enough to increase the temperature).

✓ The thermocouple is inserted back into the pipette and the temperature is measured.

✓ *SAR* will be calculated using the following formula:

$$SAR = c\frac{\Delta T}{\Delta t}$$

c - tissue specific heat (kcal/kg°C); Δt – exposure time; ΔT - difference between the two temperatures measured by thermocouple; (1kcal =4186 Joules).

Limits

➢ This method presents some difficulties due to the use of the pipette:

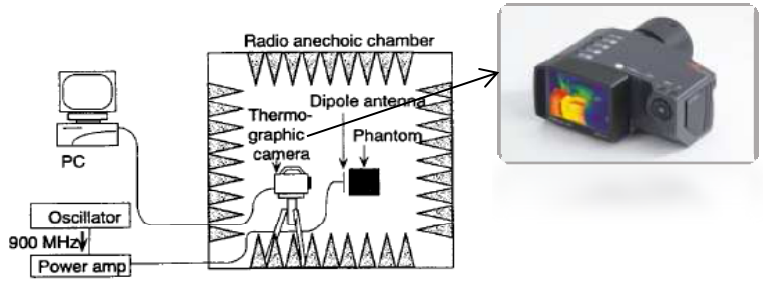
- the choice of the area where the pipette must be implanted
- the coincidence between the implantation area and the maximum absorption area
- the need to implant more than one pipette makes the measurement slow and troublesome

! Recently several probes have been tested for temperature measurements without using pipettes. This probes are made of fiber optics or use special thermistor materials. They can be used during the irradiation because the heat produced by the currents induced on the probe is negligible.

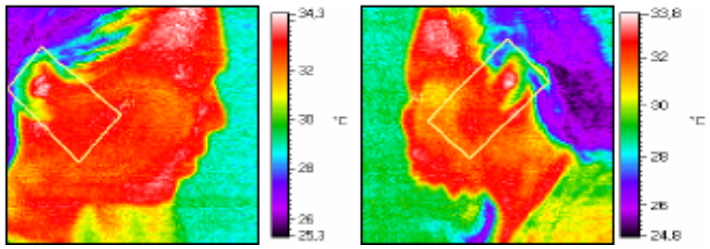
Thermographic camera

• The temperature distribution on a surface can be registered using a thermographic camera, and SAR can be determined:

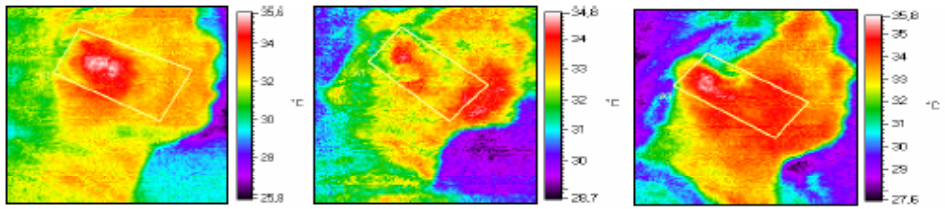
$$SAR = c\frac{\Delta T}{\Delta t}$$



• the temperature rise in ear-skull region caused by different commercial mobile phone was investigated using a thermographic camera.
• measurements were performed on a real person using the phone on the right side of the head
• picture of right and left side of the head were taken before exposure for reference
• thermal images were acquired after 15 min and 30 min of exposure immediately after the phone was removed from the head
• the acquired thermal image sequences are post processed and temperatures as a function of time are calculated. Average temperature is determined in a region of interest (ROI).



Thermal images before exposure: right side and left side of the subject



Thermal images on the right side of the subject after 30 minutes exposure to different mobile phone: Nokia 3610, Samsung SGH300 and SonyEricson T230

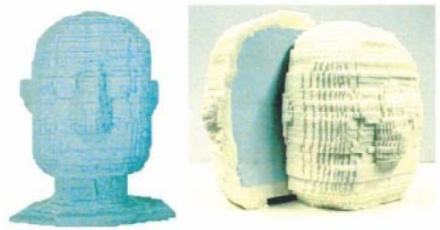
	Max value of head temperature					
Manufacture	**Reference**		**15min exposure**		**30min exposure**	
	Right	**Left**	**Right**	**Left**	**Right**	**Left**
Nokia 3610	34.2	33.8	34.2	34.3	35.8	34.5
Samsung SGH 300	34.2	33.8	34.9	34	35.6	34.9
SonyEricson T230	34.2	33.8	34.5	34.3	35.3	34.5

[A. Rusnani, N. Norsuzila, "Measurement and analysis of temperature rise caused by handheld mobile telephones using infrared thermal imaging", IEEE Trans. RF and Microwave Conf., December 2008.]

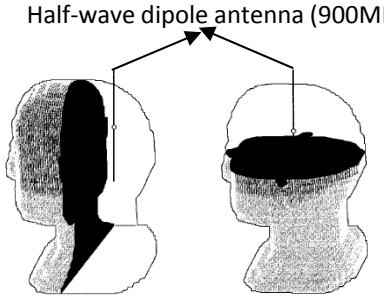
SAR distribution

• Realistic human head-phantom having brain and skull-equivalent characteristics were used to evaluate the *SAR* around an earlobe when the *MW* is irradiated to the side of a human head.
• The phantom was split to observe the inside of phantom before the exposure.
• A phantom with a uniform temperature placed in an anechoic chamber was exposed to UHF radio waves radiated by a nearby source for a short time 30s (the antenna input power 30W). The exposure duration is determined to yield a temperature rise of at least 1°C.
• After the exposure, the precut parts of the phantom are quickly separated and a thermographic image was immediately taken to map the temperature rise profile on a section or surface of the phantom and SAR due to the absorbed energy was estimated

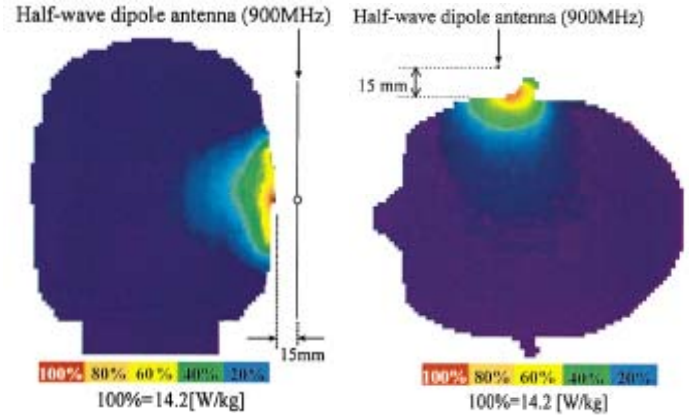
$$SAR = c\frac{\Delta T}{\Delta t}$$ c – phantom material specific heat (J/kg·°C) (brain: 3750J/kg·°C; skull 2850J/kg·K), ΔT(°C), Δt (seconds)



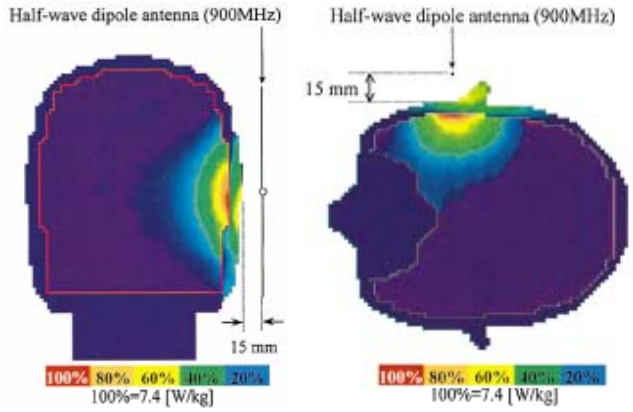
Realistic human head model: homogenous and single-layered



Observation planes : vertical and horizontal



Homogenous phantom



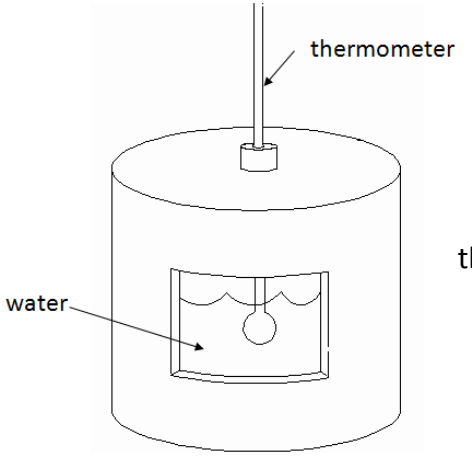
Single-layered phantom

Local peak SAR is located at the bottom of the earlobe.

Y. Okano, K. Ito, I. Ida, M. Takahashi, "The SAR evaluation method by a combination of thermographic experiments and biological tissue-equivalent phantoms", IEEE Trans. on MTT, vol. 48, no. 11, November 2000.

Calorimeter

Calorimetric methods are based on the measurement of the amount of heat transferred by the animal to a calorimeter.



First phase: the amount of energy transferred to the calorimeter by the animal without being exposed to an EM field is measured:

$$Q_b = Q_a + Q_c$$

Q_b: the heat transferred by the animal

Q_a: the heat absorbed by the calorimeter water

Q_c: the heat absorbed by the calorimeter walls

$$Q_a = m_a c_a \left(T_f - T_i\right)$$

$$Q_c = C_c \left(T_f - T_i\right)$$

- m_a - water mass
- $c_a = 4186 J/kg \cdot °C$ - water specific heat
- C_c - calorimeter heat capacity $[J/K]$

$$\Rightarrow \boxed{Q_b = \left(m_a c_a + C_c\right)\left(T_f - T_i\right)} \quad (1)$$

Second phase: the animal is exposed to an EM field for a short time Δt and then placed into the calorimeter. The amount of energy transferred to the calorimeter by the animal is measured:

$$Q_b' = Q_b + SAR_{av} \cdot m\Delta t = Q_a' + Q_c'$$

$$Q_a' = m_a c_a \left(T_f' - T_i'\right)$$

$$Q_c' = C_c \left(T_f' - T_i'\right)$$

(2)

from (1)&(2) $\Rightarrow$

$$\boxed{SAR_{av} = \frac{\left(m_a c_a + C_c\right)\left(T_f' - T_i' - T_f + T_i\right)}{m\Delta t}}$$

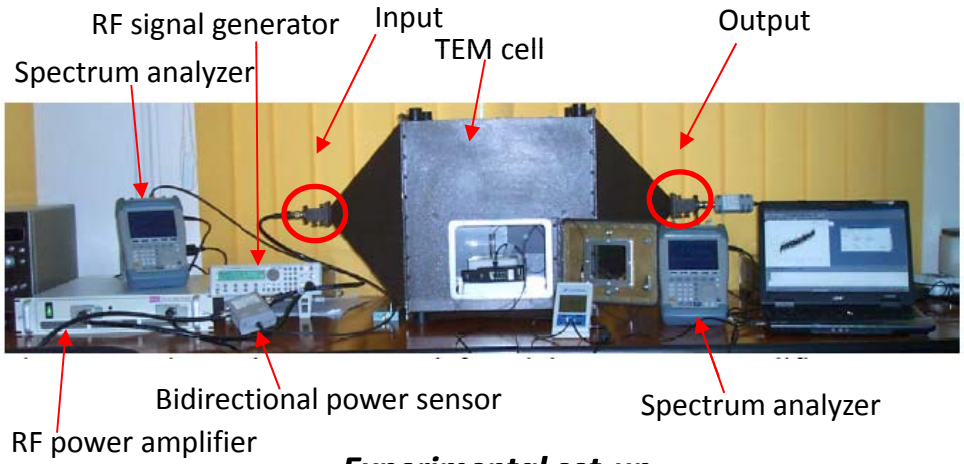
m - animal mass

Δt – exposure time

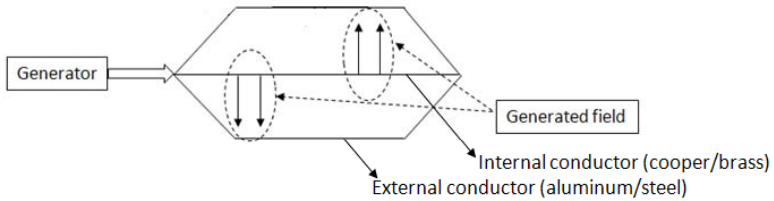
Absorbed power measurements

TEM (Transverse ElectroMagnetic) cell:

- most used system in bioelectromagnetic experiments, EMC investigations
- exposure system main characteristics:
  - generation of uniform field or a homogeneous plane wave
  - it has a usable cell volume to place biological samples
  - it is shielded from electromagnetic influence both from outside and inside
  - it operates over a wide frequency band
  - field strength can be computed from radiofrequency power travelling the cell
  - TEM cell shows cavity effects, like resonances at frequencies at which the cell dimensions are about half the wavelength.



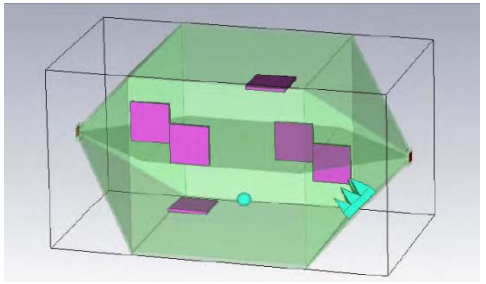
Experimental set-up



TEM cell

- Continuous RF wave from generator is amplified by the RF amplifier and fed to the cell's input port through the bidirectional power sensor, to measure both the input power (P_{in}) and reflected power (P_{refl}).
- A second power sensor connected to the cell's output measures the transmitted power (P_{out}).
- Absorbed power is calculated as the difference between the power generated to the cell and the reflected and transmitted power :

$$P_{abs} = P_{in} - P_{refl} - P_{out}$$



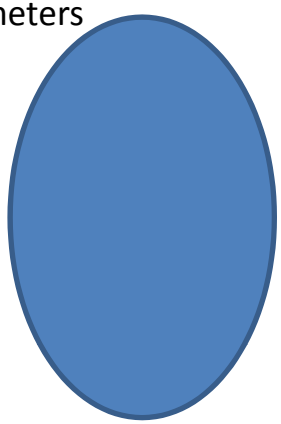
[C. Iftode, S. Miclaus, P. Bechet, E. Surducan, "A TEM cell model analysis for radiofrequency dosimetry improvement by computational means", Int. Symp. on Adv. Topics in El. Eng. , Bucharest-Romania, May 2011.]

Physical scaling

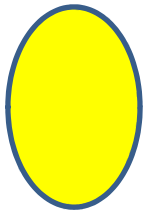
L_b – body size
σ_b and ε_b - body dielectric parameters
f_b – body experiment frequency

L_m – model size
σ_m and ε_m - model dielectric parameters
f_m – model experiment frequency

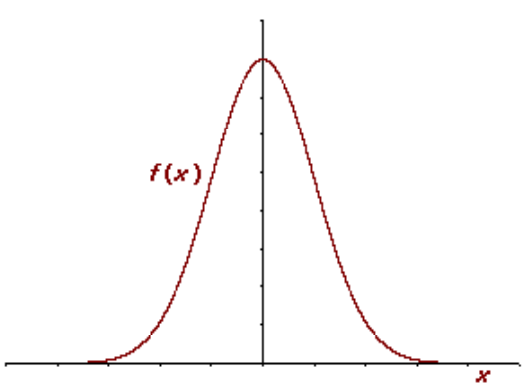
$$\tilde{\varepsilon}_b(\omega_b) = \varepsilon_b' - j\varepsilon_b'' = \varepsilon_b' - j\frac{\sigma_b}{\omega_b \varepsilon_0}$$

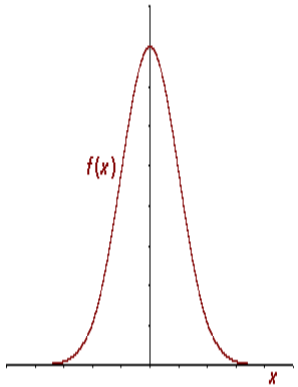


Scale factor α
Ex: 50% reduction



$$\tilde{\varepsilon}_m(\omega_m) = \varepsilon_m' - j\varepsilon_m'' = \varepsilon_m' - j\frac{\sigma_m}{\omega_m \varepsilon_0}$$





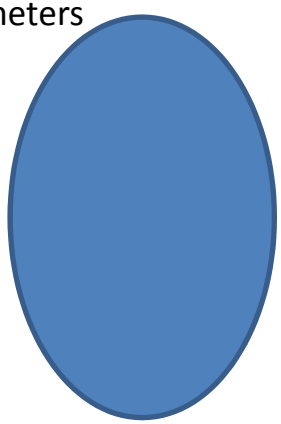
During the physical scaling the electric length (L/λ, λ=c/f), object shape and complex dielectric permittivity (ε'-jε'') need to be preserved: it follows that for the same incident field amplitude, the internal field will be equal except for the "spatial scale factor" α. Therefore, the local SAR will be equal too, if body and model have the same mass density.

Physical scaling

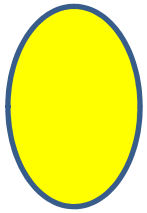
L_b – body size
σ_b and ε_b - body dielectric parameters
f_b – body experiment frequency

L_m – model size
σ_m and ε_m - model dielectric parameters
f_m – model experiment frequency

$$\tilde{\varepsilon}_b(\omega) = \varepsilon_b' - j\varepsilon_b'' = \varepsilon_b' - j\frac{\sigma_b}{\omega_b \varepsilon_0}$$



Scale factor α
Ex: 50% reduction



$$\tilde{\varepsilon}_m(\omega) = \varepsilon_m' - j\varepsilon_m'' = \varepsilon_m' - j\frac{\sigma_m}{\omega_m \varepsilon_0}$$

$$\begin{cases} L_b / \lambda_b = L_m / \lambda_m \Rightarrow f_m = f_b \dfrac{L_b}{L_m} \\ \tilde{\varepsilon}_b(\omega_b) = \tilde{\varepsilon}_m(\omega_m), \text{ with } \omega_b \neq \omega_m \end{cases} \Rightarrow \begin{cases} \varepsilon_m'(\omega_m) = \varepsilon_b'(\omega_b) \\ \sigma_m(\omega_m) = \dfrac{\omega_m}{\omega_b}\sigma_b(\omega_b) = \sigma_b(\omega_b)\dfrac{L_b}{L_m} \end{cases}$$

Last conditions cannot easily met; then the SAR distributions will only be similar in the two bodies (human body and phantom, or human body and animal), but not equal, as the complex permittivity of the biological tissues varies significantly with frequency.

References

1. P.S. Hall, Y. Hao, “Antennas and propagation for body-centric communication”, *Artech House*, 2006.
2. K. Ito, K. Furuya, Y. Okano, L. Hamada, “Development and characteristics of a biological tissue-equivalent phantom for microwaves”, *Electronics and Communications*, vol. 84, no. 4, pp. 67-77, December 2001.
3. D. Andreuccetti, M. Bini, A. Checcucci, A. Ignesti, L. Millanta, R. Olmi, N. Rubino, “Protezione dai campi elettromagnetici non ionizzanti”, 3a Edizione, *IROE “Nello Carrara” CNR*, Firenze 2001.
4. G.A. Lovisolo, R. Pinto, L. Ardoino, S. Mancini, “Dosimetria sperimentale: banco di test per dispositivi radiomobili e caratterizzazione di sistemi espositivi per sperimentazione biologica”, *Convegno Nazionale "Strumenti e tecniche di misura per la protezione dell'uomo e dell'ambiente dai campi elettromagnetici"*, Sesto Fiorentino (FI), 28-29 maggio 2003.
5. G.A. Lovisolo, R. Pinto, D. Asta, S. Mancini, “Valutazione dell’efficacia degli auricolari nella riduzione dell’esposizione ai campi elettromagnetici emessi dai telefoni cellulari”, *Energia, ambiente e innovazione*, 3, pp. 86-87, 2001.
6. http://www.sarvalues.com/measuring-sar.html
7. A. Polichetti, E. Bortolin, R. Pinto, S. Mancini, G. A. Lovisolo, P. D’Atanasio, A. Zambotti, A. Moro, G. Antonucci, “Campi elettromagnetici emessi dai telefoni cellulari: verifica dell’efficacia schermante e protettiva di dispositivi commerciali”, *Atti del Convegno Nazionale “Problemi e tecniche di misura degli agenti fisici in campo ambientale”*, Ivrea, Aprile 2001.
8. A. Hirata, M. Kojima, H. Kawai, Y. Yamashiro, S. Watanabe, H. Sasaki, O. Fujiwara, “Acute dosimetry and estimation of threshold-inducing behavioral signs of thermal stress in rabbits at 2.45GHz microwave exposure”, *IEEE Trans. On Biomed. Eng.*, vol. 57, no. 5, May 2010.
9. A. Rusnani, N. Norsuzila, “Measurement and analysis of temperature rise caused by handheld mobile telephones using infrared thermal imaging*”, IEEE Trans. RF and Microwave Conf.*, December 2008.
10. Y. Okano, K. Ito, I. Ida, M. Takahashi, “The SAR evaluation method by a combination of thermographic experiments and biological tissue-equivalent phantoms”, *IEEE Trans. on MTT*, vol. 48, no. 11, November 2000.
11. C. Iftode, S. Miclaus, P. Bechet, E. Surducan, “A TEM cell model analysis for radiofrequency dosimetry improvement by computational means”, *Int. Symp. on Adv. Topics in El. Eng.* , Bucharest-Romania, May 2011.]