HF Dosimetry

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Dosimetry in HF region

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

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

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

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

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

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

typically extrapolated from the measurement data below 20 GHz

recent research gave the data of the tissues over surface of the body. (skin and eye tissues)
Recent update on the electrical properties in HF region (1/2)

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

schematic view of skin and eye tissues (ICRP, 2002)
Recent update on the electrical properties in HF region (2/2)

Large discrepancy appears in skin tissues.

Sasaki et al., PMB, 2014

Sasaki et al., PMB, 2015
Human modeling in HF region

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

- **Numerical human models are one of the most important advances in the dosimetry, which have fine spatial resolutions with accurate anatomical structure based on CT and MRI technology.**

- Physical human phantoms have relatively poor anatomical structure, frequently consist of single material such as tissue-equivalent liquid. However the physical human phantoms have widely been used in the compliance evaluations of radio devices because actual radio devices can be used for the evaluation and the simple phantom can provide highly-reproducible and worst-side evaluation.
Latest numerical human models

From the homepage of IT’IS foundation.

France-Japan research project (FETUS)

NICT’s voxel human models.

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

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

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

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

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

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

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

Other factors to be considered.
Thermal Dosimetry for whole-body exposure: back exposed at 100 MHz

Whole-body average (WBA) SAR at 0.68 W/kg for duration of 45 min.

- Measured $\Delta T = 0.15 - 0.20 \, ^\circ C$ (100 MHz) Adair
- Computed $\Delta T = 0.177 \, ^\circ C @ 28 \, ^\circ C$ (65 MHz) unpublished
- Computed $\Delta T = 0.17 \, ^\circ C @ 28 \, ^\circ C$ (100 MHz) by Nelson

Adair et al, Bioelectromagnetics, 2003
In the elderly, thermoregulatory response is weaker than that in the young adult due to declined heat sensitivity etc, resulting in higher core temperature.

Local temperature elevation in anatomical head models

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

- Wang and Fujiwara (IEEE MTT, 1999)
- Bernardi et al. (IEEE MTT, 2000)
- Gandhi et al. (IEEE MTT, 2001)
- Hirata et al. (IEEE EMC, 2003)
- Samaras et al. (IEEE EMC, 2007)
- McIntosh et al. (BEMS, 2010)
Effect of averaging mass: Averaged SAR vs Temperature Elevation

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

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

Alekseev et al, BEMS, 2005
<table>
<thead>
<tr>
<th>Tissue</th>
<th>Heating Factor °C/W kg⁻¹ kg⁻¹</th>
<th>Frequency GHz</th>
<th>Averaging</th>
<th>Exposure data</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brain</td>
<td>0.13</td>
<td>1, 2.5, 5, 0.9-2.45</td>
<td>cube, 10 g</td>
<td>Plane wave, upfront, female adult</td>
<td>Laakso 2009</td>
</tr>
<tr>
<td></td>
<td>0.18</td>
<td></td>
<td>cube, 10 g</td>
<td>Near field averages, adult</td>
<td>Fujimoto et al. 2006</td>
</tr>
<tr>
<td></td>
<td>0.22 ¹</td>
<td></td>
<td>cube, 10 g</td>
<td></td>
<td>Van Leeuwen 1999</td>
</tr>
<tr>
<td></td>
<td>0.21</td>
<td>0.915</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eye</td>
<td>0.1 -0.12 (lens)</td>
<td>1-3, 7.5, 0.6-3, 5, 0.9-1.9</td>
<td>cube, 10 g</td>
<td>Plane wave averages, male</td>
<td>Laakso 2009</td>
</tr>
<tr>
<td></td>
<td>0.13 (lens)</td>
<td></td>
<td></td>
<td></td>
<td>Hirata et al. 2007</td>
</tr>
<tr>
<td></td>
<td>0.11-0.147 (lens)</td>
<td></td>
<td></td>
<td></td>
<td>Hirata 2005</td>
</tr>
<tr>
<td></td>
<td>0.22 (lens)</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>0.16-0.17 (lens)</td>
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</tr>
<tr>
<td></td>
<td>0.18-0.19</td>
<td>0.380-1.8, 1, 3</td>
<td>eye, 9.4 g, cube, 10 g</td>
<td>Near fields and plane wave</td>
<td>Wainwright 2007</td>
</tr>
<tr>
<td></td>
<td>0.21</td>
<td></td>
<td></td>
<td></td>
<td>McIntosh et al. 2010</td>
</tr>
<tr>
<td></td>
<td>0.23</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skin, fat, pinna, muscle</td>
<td>0.2-0.26</td>
<td>1-3, 6</td>
<td>cube, 10 g</td>
<td>Plane wave and near fields</td>
<td>McIntosh et al. 2010</td>
</tr>
<tr>
<td></td>
<td>0.28-0.37</td>
<td></td>
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</tbody>
</table>
Fig. 1. Incident power density sufficient to increase skin temperature by 10°C, considered to be the threshold for thermal pain. Also shown are IEEE C95.1-2005 and ICNIRP exposure limits.

Alekseev et al, Bioelectromagn., 2005

Foster et al, Health Phys., 2010
Thermal Time Constants for Local and Whole-body Exposures

- 1D (fat)
- 1D (skin)
- ICNIRP
- 3D model

IEEE

\[ \text{WBA-SAR} = 0.4 \, \text{W/kg} \]

Foster et al, Bioelectromagnetics, 1998
Threshold of perception and pain due to contact current

- Above 100 kHz, heat sensation. Below 100 kHz, sensation of electrostimulation.
- Pain threshold in finger may reach the heat perception threshold after 10-20 s.
- Pain is due to the stimulation of nociceptors in the cutaneous and subcutaneous tissues.
- Skin temperature elevation from 34 to 36 °C at rate of 4°C/s elicits a pain sensation (Green et al. 2010).
Local SAR induced by contact current of 40 mA in finger of an adult

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>$\text{SAR}_{10g}$ (W/kg) $^1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>468</td>
</tr>
<tr>
<td>1</td>
<td>393</td>
</tr>
<tr>
<td>10</td>
<td>469</td>
</tr>
<tr>
<td>100</td>
<td>387</td>
</tr>
</tbody>
</table>

$^1$ IEEE averaging scheme

Extremely high SAR in finger

40 mA=ICNIRP1998 reference level for occupational exposure

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

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

Summary

Measured data
Tissue properties

Numerical Human
body models

HF Dosimetry
Electromagnetics, Thermodynamics

Uncertainty

Threshold assessment
Metric

Temperature elevation

Measured data

Uncertainty

Reduction Factor

Reference Level

Basic restriction
ICNIRP Guidelines above 300 GHz (Laser)

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Exposure duration</th>
<th>Exposure limit (W m(^{-2}) or J m(^{-2}))</th>
<th>Exposure limit (W or J)</th>
<th>Restrictions</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 600 ≤ λ &lt; 1 mm</td>
<td>100 ns</td>
<td>10 s</td>
<td>5.6 (0.25) kJ m(^{-2})</td>
<td></td>
</tr>
<tr>
<td>1 400 ≤ λ &lt; 1 mm</td>
<td>10 s</td>
<td>30 ks</td>
<td>1.0 kW m(^{-2})</td>
<td></td>
</tr>
<tr>
<td>1 800 ≤ λ &lt; 2 600</td>
<td>1 ms</td>
<td>10 s</td>
<td>10 kJ m(^{-2})</td>
<td></td>
</tr>
<tr>
<td>1 500 ≤ λ &lt; 1 800</td>
<td>1 ns</td>
<td>10 s</td>
<td>5.6 (0.25) kJ m(^{-2})</td>
<td></td>
</tr>
<tr>
<td>1 400 ≤ λ &lt; 1 500</td>
<td>1 ms</td>
<td>10 s</td>
<td>1.0 kJ m(^{-2})</td>
<td></td>
</tr>
<tr>
<td>2 600 ≤ λ &lt; 1 mm</td>
<td>1 ns</td>
<td>100 ns</td>
<td>100 kJ m(^{-2})</td>
<td></td>
</tr>
</tbody>
</table>

\(^{a,b}\)
<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Exposure duration</th>
<th>Exposure limit</th>
<th>Restrictions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ultraviolet</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>$180 \leq \lambda &lt; 400$</td>
<td>1 ns</td>
<td>30 ks</td>
<td>Same as EL for the eye</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>See Table 5</td>
</tr>
<tr>
<td>$400 \leq \lambda &lt; 1,400$</td>
<td>100 ns</td>
<td>10 s</td>
<td>$200 \frac{C_A}{m^2}$</td>
</tr>
<tr>
<td>$400 \leq \lambda &lt; 1,400$</td>
<td>10 s</td>
<td>30 ks</td>
<td>$11 \frac{C_A}{m^{0.25}}$</td>
</tr>
<tr>
<td>$400 \leq \lambda &lt; 1,400$</td>
<td></td>
<td></td>
<td>$2.0 \frac{C_A}{W/m^2}$</td>
</tr>
<tr>
<td><strong>Visible and short wavelength IRR</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$400 \leq \lambda &lt; 1,400$</td>
<td>1 ns</td>
<td>100 ns</td>
<td>$3.5 \text{ mm limiting aperture}^b$</td>
</tr>
<tr>
<td>$400 \leq \lambda &lt; 1,400$</td>
<td>10 s</td>
<td>30 ks</td>
<td></td>
</tr>
<tr>
<td><strong>Mid and long wavelength IRR</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$1,400 \leq \lambda &lt; 1 \text{ mm}$</td>
<td>1 ns</td>
<td>30 ks</td>
<td>Same as EL for the eye</td>
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<td></td>
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