Biological Considerations for Setting Exposure limits Above 6 GHz

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Millimeter Wave Therapy

“Therapeutic” wavelengths:
4.9, 5.6, and 7.1 mm
(frequencies 61.22, 53.57 and 42.25 GHz)

Exposure of patient’s skin:
acupuncture points, forehead, occiput
sternum; big joints, surgical wounds

Use to treat thousands of patients in the Former Soviet Union for many diseases
Millimeter Wave Irradiation

- Heating is a Major Mechanism for Bioeffects
- Most of Energy is Absorbed within a Few Tenths of a Millimeter
- Wavelengths in Tissue are Comparable with Biological Structures
- Irradiation is frequently in the Near Field
IR-camera measurements of mm-wave heating of phantom with YAV devices

Phantom- 0.2 mm thick saline saturated filter paper absorber
Skin phantom

Human skin

Heating patterns resulting from mm-wave irradiation from the open side of a rectangular waveguide under similar exposure conditions
CONCLUSIONS

• Millimeter waves can produce non-uniform heating patterns in irradiated objects, especially when these objects are irradiated in the near-field area.

• SAR values in hot-spots area can exceed 500 W/kg at 10 mW/cm² average incident power density.
Specific Absorption Rate (SAR)

For RF Standards:

• SAR is chosen over Power Density because it is a better predictor of Biological Effects

• But not for frequencies greater than \( \sim 6 \) GHz, where penetration is limited to skin.
Millimeter wave irradiation used in therapy, if sufficiently intense, can activate thermo-receptors and free nerve endings in the outer layers of the skin.

Typical therapeutic exposures = $10 - 20 \text{ mW/cm}^2$

No sensation for exposures $< 40 \text{ mW/cm}^2$

No pain for exposures $< 100 \text{ mW/cm}^2$
# Epidermis

(150 – 200 μm Thick)

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness (μm)</th>
<th>Water (per cent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Horn eye</td>
<td>13 - 15</td>
<td>2</td>
</tr>
<tr>
<td>2. Clear</td>
<td>0 - 20</td>
<td>10-45</td>
</tr>
<tr>
<td>3. Granular</td>
<td>10 - 20</td>
<td>10-47</td>
</tr>
<tr>
<td>4. Prickle Cell</td>
<td>85 - 115</td>
<td>72</td>
</tr>
<tr>
<td>5. Basal Cell</td>
<td>15 - 18</td>
<td>72</td>
</tr>
<tr>
<td>Selected Frequency (GHz)</td>
<td>Skin Depth (mm)</td>
<td></td>
</tr>
<tr>
<td>--------------------------</td>
<td>-----------------</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>4.09</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1.90</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>0.43</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>0.24</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>0.14</td>
<td></td>
</tr>
</tbody>
</table>
ANATOMY OF THE SKIN

Epidermis
150 µm

94-GHz Penetration Depth

Dermis

35-GHz Penetration Depth

Free nerve ending
## Skin Thickness

<table>
<thead>
<tr>
<th>Region</th>
<th>Epidermis (μm)</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eyelid</td>
<td>58</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Postauricular Region</td>
<td>69</td>
<td>65</td>
<td></td>
</tr>
<tr>
<td>Back</td>
<td>88</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Forehead</td>
<td>96</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>Back of Arm</td>
<td>101</td>
<td>73</td>
<td></td>
</tr>
<tr>
<td>Cheek</td>
<td>115</td>
<td>85</td>
<td></td>
</tr>
<tr>
<td>Buttock</td>
<td>148</td>
<td>128</td>
<td></td>
</tr>
<tr>
<td>Dorsum of Foot</td>
<td>180</td>
<td>175</td>
<td></td>
</tr>
<tr>
<td>Dorsum of Hand</td>
<td>247</td>
<td>132</td>
<td></td>
</tr>
<tr>
<td>Palm</td>
<td>557</td>
<td>647</td>
<td></td>
</tr>
<tr>
<td>Sole</td>
<td>793</td>
<td>478</td>
<td></td>
</tr>
<tr>
<td><strong>AVERAGE</strong></td>
<td><strong>223</strong></td>
<td><strong>180</strong></td>
<td></td>
</tr>
</tbody>
</table>
Effect of Age on Skin

Skin of Infant

Skin is completely formed at birth

Stratum corneum is thinner and Water content is higher.

Papillary dermis is thinner than in adults

Production of sweat is reduced
Effect of Age on Skin

Skin of a Child

After reaching one year of age, the skin of a child is essentially the same as that of an adult.
Effect of Age on Skin

Skin in Elderly

Epidermis thins

Blood vessels of the dermis become more fragile

Sebum production decreases leading to increased dryness and itching

Fat layer thins leading to decreased ability to maintain body temperature

Sweat production decreases making it harder to lose heat
Skin Models

Exposure

1 2 Fat

3-Layer Model

1 2 Fat Muscle

4-Layer Model

Where

1 = Stratum Corneum
2 = Viable Epidermis + Dermis
Reflection from boundary between two tissues

\[ r_i(f) = \frac{n_i - n_{i+1}}{n_i + n_{i+1}} \]

Where

- \( r_i \) = amplitude reflection coefficient
- \( n_i \) = complex index of refraction of tissue \( i \)
- \( n_{i+1} \) = complex index of refraction of tissue \( i+1 \)
Reflection from boundary between two tissues

\[ R(f) = |r_i(f)|^2 \]

Where

\[ R(f) = \text{Power reflection coefficient} \]
\[ r_i(f) = \text{Amplitude reflection coefficient} \]
\[ R(f) = \left| \frac{r_1(f) + r_2(f) \cdot e^{j \varphi_2(f)} + r_3(f) \cdot e^{j(\varphi_2(f) + \varphi_3(f))} + r_1(f) \cdot r_2(f) \cdot r_3(f) \cdot e^{j \varphi_3(f)}}{1 + r_1(f) \cdot r_2(f) \cdot e^{j \varphi_2(f)} + r_1(f) \cdot r_3(f) \cdot e^{j(\varphi_2(f) + \varphi_3(f))} + r_2(f) \cdot r_3(f) \cdot e^{j \varphi_3(f)}} \right|^2 \]

\[ \frac{r_4(f) \cdot e^{j(\varphi_2(f) + \varphi_3(f) + \varphi_4(f))} + r_1(f) \cdot r_2(f) \cdot r_4(f) \cdot e^{j(\varphi_3(f) + \varphi_4(f))} + r_1(f) \cdot r_4(f) \cdot e^{j(\varphi_2(f) + \varphi_3(f) + \varphi_4(f))} + r_2(f) \cdot r_4(f) \cdot e^{j(\varphi_3(f) + \varphi_4(f))} + r_3(f) \cdot r_4(f) \cdot e^{j \varphi_4} (r_1(f) + r_2(f) \cdot e^{j \varphi_2(f)})}{r_3(f) \cdot r_4(f) \cdot e^{j \varphi_4} + r_1(f) \cdot r_2(f) \cdot r_3(f) \cdot r_4(f) \cdot e^{j(\varphi_2(f) + \varphi_4(f))}} \]
<table>
<thead>
<tr>
<th>Parameter</th>
<th>3-layer model</th>
<th>4-layer model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SC</td>
<td>E+D</td>
</tr>
<tr>
<td>$\varepsilon_\infty$</td>
<td>2.96</td>
<td>4.0</td>
</tr>
<tr>
<td>$\Delta \varepsilon$</td>
<td>1.5±0.2</td>
<td>32.4±4.7</td>
</tr>
<tr>
<td>d, mm</td>
<td>0.015</td>
<td>1.45</td>
</tr>
<tr>
<td>$\sigma$, S/m</td>
<td>0</td>
<td>1.4</td>
</tr>
<tr>
<td>$\tau \times 10^{12}$, s</td>
<td>6.9</td>
<td>6.9</td>
</tr>
</tbody>
</table>
Tissue models used for thermal modeling of mm wave heating

Exposure

- Homogeneous tissue
  - Model 1

- Skin | Fat | Muscle
  - Model 2

- E | D | Fat | Muscle
  - Model 3

E - Epidermis
D - Dermis
Temperature measurements in the skin during mm-wave exposure with WG opening

Lower forearm

Index finger

Generator G4-141

Frequency: 42.25 GHz
Output power: 52 mW
IR images show the forearm skin at 0, 10, 30, and 55 s following exposure with the WG ($I_o = 208 \text{ mW/cm}^2$). The distance between the open end of WG and skin surface was 2.5 mm. The lighter band on the bottom of each thermogram corresponds to the warmer skin area located above a vein. Baseline skin temperature was 32.5 °C. Maximum temperature at 55 s was 35.7 °C.
Temperature rise rate profiles at d=2.5 mm from waveguide opening.

\[ \Delta T / \Delta t \] °C/s

\[ \begin{align*}
I_x &= I_o \exp(-ax^2) \\
a &= 20 \text{ cm}^{-2}
\end{align*} \]

\[ \begin{align*}
I_y &= I_o \exp(-by^2) \\
b &= 14.5 \text{ cm}^{-2}
\end{align*} \]

\[ c = \sqrt{ab} = 17 \text{ cm}^{-2} \]
Skin Exposure Modes

1-D Model

\[ Q(z) = q_o \times e^{-\frac{2z}{\delta}} \]

\( \delta = 0.056 \text{ cm} \)

2-D Model

\[ Q(r, z) = q_o \times e^{-cr^2} \times e^{-\frac{2z}{\delta}} \]

\( c = 17 \text{ cm}^{-2} \text{ WG} \)

\( c = 3.7 \text{ cm}^{-2} \text{ YAV} \)

Heat input from exposure:
Heat Transport Equations in the Skin

1-D:
\[
\frac{\rho C}{k} \frac{\partial T}{\partial t} \times \frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial z^2} - \frac{V_s}{k} \times (T - T_b) + Q(z)
\]

2-D:
\[
\frac{\rho C}{k} \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2} + \frac{\partial^2 T}{\partial z^2} - \frac{V_s}{k} \times (T - T_b) + Q(z, r)
\]

\(\rho\) – tissue density  
\(C\) – specific heat  
\(k\) – heat conduction coefficient  
\(T\) – tissue temperature  
\(T_b\) - arterial blood temperature  
\(V_s\) – product of blood flow and heat capacity  
\(Q\) – heat input from mm-wave exposure
Temperature rise kinetics measured at the skin surface during mm-wave exposure with YAV device \((I_0 = 54.9 \text{ mW/cm}^2)\) or waveguide opening \((I_0 = 208 \text{ mW/cm}^2)\) and fitting to model.
Temperature distributions in multilayer tissue model with a fat thickness of 1, 2, or 4 mm after exposure to 42 GHz at 20 mW/cm$^2$.

Epidermis - 0.1 mm
Dermis - 1.5 mm
Effective Thermal Conductivity

\[ k_{\text{eff}} = k \cdot (1 + \beta \cdot BF) \]

where

- \( K_{\text{eff}} \) = Effective thermal conductivity
- \( K \) = True thermal conductivity
- \( B \) = 975 \((\text{ml} / \text{s} / \text{ml})-1\)
- \( BF \) = Blood Flow
# Effective Thermal Conductivity

<table>
<thead>
<tr>
<th>Body Site</th>
<th>Blood Flow</th>
<th>$k_{\text{eff}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forehead</td>
<td>$7.2 \cdot 10^{-3}$</td>
<td>2.57</td>
</tr>
<tr>
<td>Face</td>
<td>$12.0 \cdot 10^{-3}$</td>
<td>4.06</td>
</tr>
<tr>
<td>Thorax</td>
<td>$1.1 \cdot 10^{-3}$</td>
<td>0.66</td>
</tr>
<tr>
<td>Abdomen</td>
<td>$1.4 \cdot 10^{-3}$</td>
<td>0.76</td>
</tr>
<tr>
<td>Forearms</td>
<td>$0.3 \cdot 10^{-3}$</td>
<td>0.41</td>
</tr>
<tr>
<td>Hands</td>
<td>$3.3 \cdot 10^{-3}$</td>
<td>1.35</td>
</tr>
</tbody>
</table>
Pain Thresholds and Safety Margins

- Normal Skin Temperature = 34 °C
- Pain Threshold = 44-45 °C
- First Degree Burn = 55-60 °C
- Second Degree Burn = 60-65 °C
- Third Degree Burn = >70 °C
Setting Exposure Limits Above 6 GHz

For Acute Effects:

Temperature elevation – duration concerns are important.

But:

Unlimited duration exposures must be considered.
Setting Exposure Limits Above 6 GHz

Temperatures $< 40 \, ^\circ\text{C}$ will not damage skin.

For example, consider hot tubs and Jacuzzi’s.
Setting Exposure Limits Above 6 GHz

In addition to skin damage, protect people from bodily harm.

Insure that core temperature rises < 1 °C
Setting Exposure Limits Above 6 GHz

For core temperature to rise > 1°C:

Exposures greater than 6 GHz would have to be:

Whole body
Prolonged
Produce a skin temperature ~ 40°C
Setting Exposure Limits Above 6 GHz

To keep core temperature $< 1 \degree C$

Keep skin temperatures $< 37 \degree C$, $A$ rise of $\sim 4 \degree C$ under most conditions

Use appropriate skin model(s) to accomplish this
Setting Exposure Limits Above 6 GHz

Keep brain temperature rise \(< 0.5\, ^\circ C\)

Daily circadian temperature rise = 0.5 \(^\circ\)C

Use appropriate skin model(s) to accomplish this
Thank You