Ocular Studies of EMF Exposure at the MMW

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MMW Exposure System

- Power source
- Directional coupler
- Power sensor A
- Directional coupler
- Power sensor B
- Power meter (E4417A, Agilent Technologies)
- Horn antenna
- φ-15cm lens
- Thermography camera
- Red Laser
- Green Laser
- Lens Antenna
- Discerned: 135mm

Eyelids held open with tape

Lens antenna
Exposure Conditions
(aversive behavior control)

- Eyelids unrestrained

- Eyelid edema occurs, but no ocular damage
  (Ex. 75 GHz 200 mW/cm² 6 min 1 day after exposure)

- Without control of aversive behavior
  Without control of aversive behavior, ocular the damage threshold depends on by the skin hazard threshold.
Representative Ocular Damages by 75 GHz 200 mWcm$^2$ Exposure

**Anterior segment photo**

- **Before Expo.**
- **10 min. after Expo.** Miosis+
- **1 day after Expo.**
- **2 days after Expo.**
- **3 days after Expo.**

**Cornea OCT image**

- Before Expo.: 0.37, 0.36, 0.38
- 10 min. after Expo.: 0.29, 0.29, 0.29
- 1 day after Expo.: 0.43, 0.56, 0.47
- 2 days after Expo.: 0.41, 0.43, 0.41
- 3 days after Expo.: 0.40, 0.40, 0.39

**Fluorescein staining**

- Corneal epithelial cell damage (surface)
- Corneal stromal damage (inflammation)
Confocal Laser Scanning Microscopy Findings
Immediately after 40 GHz, 600 mW/cm² exposure

Fluorescein Staining  Corneal Epithelial Layer  Corneal Endothelial Layer
Four Days after 40 GHz, 600 mW/cm² Exposure

Exposed

Non-exposed

0.44 mm

0.33 mm
Confocal Laser Scanning Microscopy Findings
Four days after 40 GHz, 600 mW/cm² exposure: epithelial layer

Exposed
Four Days after 40 GHz, 600 mW/cm$^2$ Exposure: endothelial layer

Exposed

Non-exposed
MMW (40 GHz, 600 mW/cm², 6 min) did not induce any marked corneal endothelial cell damage.

Epithelium and endothelium damage showed different directions of corneal swelling.

Corneal disorder resulted primarily from corneal epithelial cell death induced by MMW exposure.

MMW exposure: Convex to epithelium side

Glaucoma attack: Convex to endothelium side
Ocular Effects of Exposure to 40, 75, and 95 GHz Millimeter Waves

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J Infrared Milli Terahz Waves
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Methods

- Rabbits were exposed to MMWs at frequencies of 40, 75, and 95 GHz for 6 minutes.
- One day after exposure, morphological changes in the cornea were assessed by slit-lamp microscopy (including fluorescence staining) and optical coherence tomography.
- Dose-response data of corneal injury (corneal epithelium damage, corneal opaque, and corneal edema) at each frequency were obtained by experiments in the range of power density.
MMW Exposure

Incident power density: Power density averaged over a 13-mm-diameter circle corresponding to the area of the ocular surface exposed to the ambient air.

Beam profile

40 GHz

13 mm diameter

FWHM: full width at half maximum

95 GHz

13 mm diameter

FWHM: full width at half maximum
## Damage by 40 GHz Exposure

<table>
<thead>
<tr>
<th>40 GHz</th>
<th>One day after exposure</th>
<th>Corneal Surface Temp. (°C)</th>
<th>Corneal Epithelium Damage</th>
<th>Corneal Opaque</th>
<th>Corneal Edema</th>
</tr>
</thead>
<tbody>
<tr>
<td>400 mW/cm²_6 min</td>
<td>43.9±3.6</td>
<td>Damage + (6/8)</td>
<td>Damage + (5/8)</td>
<td>Damage + (5/8)</td>
<td></td>
</tr>
<tr>
<td>300 mW/cm²_6 min</td>
<td>41.3±1.3</td>
<td>Damage + (5/6)</td>
<td>Damage + (1/6)</td>
<td>Damage + (1/6)</td>
<td></td>
</tr>
<tr>
<td>200 mW/cm²_6 min</td>
<td>41.3±1.5</td>
<td>Damage+ (2/4)</td>
<td>No damage (0/4)</td>
<td>No damage (0/4)</td>
<td></td>
</tr>
<tr>
<td>100 mW/cm²_6 min</td>
<td>37.1±2.7</td>
<td>Damage+ (1/7)</td>
<td>No damage (0/7)</td>
<td>No damage (0/7)</td>
<td></td>
</tr>
<tr>
<td>50 mW/cm²_6 min</td>
<td>33.6±1.8</td>
<td>No damage (0/8)</td>
<td>No damage (0/8)</td>
<td>No damage (0/8)</td>
<td></td>
</tr>
</tbody>
</table>
## Damage by 75 GHz Exposure

<table>
<thead>
<tr>
<th>75 GHz</th>
<th>Corneal Surface Temp. (°C)</th>
<th>Corneal Epithelium Damage</th>
<th>Corneal Opaque</th>
<th>Corneal Edema</th>
</tr>
</thead>
<tbody>
<tr>
<td>One day after exposure</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300 mW/cm²_6 min</td>
<td>50.7 ± 1.9</td>
<td>Damage+ (3/3)</td>
<td>Damage+ (3/3)</td>
<td>Damage+ (3/3)</td>
</tr>
<tr>
<td>200 mW/cm²_6 min</td>
<td>43.8 ± 4.9</td>
<td>Damage+ (14/15)</td>
<td>Damage+ (13/15)</td>
<td>Damage+ (13/15)</td>
</tr>
<tr>
<td>150 mW/cm²_6 min</td>
<td>43.1 ± 1.9</td>
<td>Damage+ (3/6)</td>
<td>Damage+ (3/6)</td>
<td>Damage+ (3/6)</td>
</tr>
<tr>
<td>100 mW/cm²_6 min</td>
<td>40.2 ± 0.5</td>
<td>Damage+ (1/12)</td>
<td>No damage (0/12)</td>
<td>No damage (0/12)</td>
</tr>
<tr>
<td>50 mW/cm²_6 min</td>
<td>37.6 ± 1.5</td>
<td>No damage (0/7)</td>
<td>No damage (0/7)</td>
<td>No damage (0/7)</td>
</tr>
</tbody>
</table>
# Damage by 95 GHz Exposure

<table>
<thead>
<tr>
<th>95 GHz</th>
<th>Corneal Surface Temp. (°C)</th>
<th>Corneal Epithelium Damage</th>
<th>Corneal Opaque Damage</th>
<th>Corneal Edema</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 mW/cm²_6 min</td>
<td>46.5 ± 1.3</td>
<td>Damage+ (3/3)</td>
<td>Damage+ (2/3)</td>
<td>Damage+ (1/3)</td>
</tr>
<tr>
<td>200 mW/cm²_6 min</td>
<td>43.7 ± 1.7</td>
<td>Damage+ (11/13)</td>
<td>Damage+ (5/13)</td>
<td>Damage+ (6/13)</td>
</tr>
<tr>
<td>100 mW/cm²_6 min</td>
<td>37.0 ± 3.3</td>
<td>Damage+ (1/9)</td>
<td>No damage (0/9)</td>
<td>No damage (0/9)</td>
</tr>
<tr>
<td>50 mW/cm²_6 min</td>
<td>34.1 ± 2.3</td>
<td>No damage (0/4)</td>
<td>No damage (0/4)</td>
<td>No damage (0/4)</td>
</tr>
</tbody>
</table>
Probability of Ocular Damage by Maximum Likelihood Estimation with Probit Analysis

Incident power density [mW/cm^2] (Damage Dose: DD) versus Frequency [GHz].

- DD_{90}
- DD_{50}
- DD_{10}

Key points:
- 467 at 30 GHz
- 206 at 40 GHz
- 91 at 50 GHz
- 195 at 60 GHz
- 143 at 70 GHz
- 105 at 80 GHz
- 146 at 90 GHz
- 99 at 100 GHz
Characteristics of Ocular Temperature Elevations after Exposure to Quasi- and Millimeter Waves (18-40 GHz)

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Difference in Intraocular Temperature Rise by Frequency (200 mW/cm² exposure)

Cornea

Temperature elevation (°C)

- Trend: p<0.001

Lens

Temperature elevation (°C)

- Trend: p<0.003

Vitreous

Temperature elevation (°C)

- Trend: N.S.
Comparison of Temperature Rise in the Anterior Chamber by Quasi-MMW & MMW (18 vs. 40 GHz)

Microencapsulated Thermochromic Liquid Crystals (MTLC) change color with temperature.

18 GHz
200 mW/cm²

35°C  39°C  42°C

40 GHz
200 mW/cm²

34  35  36  37  38  39  40  41  42  43  44  45 °C
Summary

• Although ocular damage induced by 40 and 75 GHz did not differ greatly, ocular damage induced by 95 GHz was more localized and milder.

• Ocular damage thresholds among 40, 75 and 95 GHz in rabbit eye are affected by the following factors: MMW penetration depth, and heat transport in the eye including dissipation from the cornea.

• The highest ocular temperature was induced by 40 GHz MMW, followed by 35 GHz. The 26.5 and 22 GHz corneal temperatures were similar. The lowest temperature was recorded at 18 GHz.

• Corneal disorder resulted primarily from corneal epithelial cell death induced by MMW exposure, whereas corneal edema and corneal opacity were secondary findings to corneal epithelial cell death.
Acknowledgment

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Discussion

Broad and deep temperature elevation causes wide convection.

Corneal surface heat generation causes an intensive convection.

Skin depth: 0.59 mm for MMW (40 GHz)

Skin depth: 0.31 mm for MMW (95 GHz)