Exposure Limits for Laser Radiation

Bruce E. Stuck

ICNIRP Member

U.S. Army Medical Research Department (Recently retired!)

San Antonio, TX
Lasers in Our Environment

- Home (compact disk players, laser printers)
- School (laser pointers, teaching optics)
- Supermarket (bar code scanners)
- Hospital (photocoagulate, burn, cut, ablate, PDT)
- Communications (fiber optics, free space)
- Entertainment (concerts, amusement parks, hotels, electronic games)
- Industry (heat, weld, cut, align, measure, count)
- Military (rangefinders, designators, illuminators, training devices)
- Security Systems
- Research Laboratories
Medical Applications of Laser Radiation

- Used in most medical specialties to:
  - Heat, burn, cut, ablate, illuminate, stimulate
- A few examples:
  - Corneal refractive surgery
    - Photo refractive keratoplasty (PRK)
    - PRK LASIK (Laser in-situ keratomileusis)
  - Photocoagulation
  - Photodisruption (secondary cataract removal)
  - Photodynamic therapy (PDT)
  - Surgery - endoscope compatible
  - Biostimulation or biomodulation
  - Fluorescence angiography
  - Imaging (SLO, Wavefront corrected retinal Imaging, OCT)
  - Alignment (MRI)
  - Doppler blood flow
  - Skin rejuvenation (fractional laser therapy)
## Common Lasers and Laser Wavelengths

<table>
<thead>
<tr>
<th>Wavelength Range (nm)</th>
<th>Laser Type</th>
<th>Wavelength(s)</th>
<th>Wavelength Range (um)</th>
<th>Laser Type</th>
<th>Wavelength(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ultraviolet</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>180-315</td>
<td>ArF Excimer</td>
<td>193</td>
<td></td>
<td>HeNe (red)</td>
<td>632.8</td>
</tr>
<tr>
<td>180-315</td>
<td>KrCl Excimer</td>
<td>222</td>
<td></td>
<td>InGaAlP</td>
<td>670nm</td>
</tr>
<tr>
<td>248</td>
<td>KrF Excimer</td>
<td>248</td>
<td></td>
<td>Krypton</td>
<td>647-676 nm</td>
</tr>
<tr>
<td>266</td>
<td>Nd:YAG(quadrupled)</td>
<td>266</td>
<td></td>
<td>Ruby</td>
<td>694.3 nm</td>
</tr>
<tr>
<td>275</td>
<td>Argon</td>
<td>275</td>
<td></td>
<td>Ti:Sapphire</td>
<td>0.7-1.0</td>
</tr>
<tr>
<td>308</td>
<td>XeCl Excimer</td>
<td>308</td>
<td></td>
<td>GaAlAs</td>
<td>0.78</td>
</tr>
<tr>
<td>351, 363</td>
<td>Krypton</td>
<td>350.7, 356.4</td>
<td></td>
<td>Alexandrite</td>
<td>0.72-0.80</td>
</tr>
<tr>
<td><strong>315-400</strong></td>
<td>Helium Cadmium</td>
<td>325</td>
<td></td>
<td>GaAlAS</td>
<td>0.85</td>
</tr>
<tr>
<td>337</td>
<td>Nitrogen</td>
<td>337</td>
<td></td>
<td>GaAs</td>
<td>0.905</td>
</tr>
<tr>
<td>351</td>
<td>XeF Excimer</td>
<td>351</td>
<td></td>
<td>Nd:Glass</td>
<td>1.060</td>
</tr>
<tr>
<td>351, 363</td>
<td>Argon</td>
<td>350.7, 356.4</td>
<td></td>
<td>Nd:YAG</td>
<td>1.064</td>
</tr>
<tr>
<td>351, 363</td>
<td>Krypton</td>
<td>350.7, 356.4</td>
<td></td>
<td>(HeNe)</td>
<td>1.080, 1.156</td>
</tr>
<tr>
<td><strong>Visible</strong></td>
<td>Helium Cadmium</td>
<td>441.6</td>
<td>1.4-1000</td>
<td>Nd:YAG</td>
<td>1.318, 1.338, 1.356</td>
</tr>
<tr>
<td>400-700</td>
<td>Argon</td>
<td>476, 488, 514.5</td>
<td>1.4-1000</td>
<td>Erbium Glass</td>
<td>1.54</td>
</tr>
<tr>
<td>511, 568</td>
<td>Copper Vapor</td>
<td>511, 568</td>
<td>1.4-1000</td>
<td>Holmium</td>
<td>2.06</td>
</tr>
<tr>
<td>530</td>
<td>Krypton</td>
<td>530</td>
<td>1.4-1000</td>
<td>Hydrogen Flouride</td>
<td>2.6-3.0</td>
</tr>
<tr>
<td>532</td>
<td>Nd:YAG (doubled)</td>
<td>532</td>
<td>1.4-1000</td>
<td>Erbium YLF</td>
<td>2.94</td>
</tr>
<tr>
<td>543</td>
<td>Helium Neon(HeNe)</td>
<td>543</td>
<td>1.4-1000</td>
<td>Deuterium Flouride</td>
<td>3.8-4.0</td>
</tr>
<tr>
<td>400-550</td>
<td>Dye (Coumarin)</td>
<td>400-550</td>
<td>1.4-1000</td>
<td>Carbon Monoxide</td>
<td>5.0-5.5</td>
</tr>
<tr>
<td>550-700</td>
<td>Dye (Rhodamine)</td>
<td>550-700</td>
<td>1.4-1000</td>
<td>Carbon Dioxide</td>
<td>10.6</td>
</tr>
<tr>
<td>594</td>
<td>HeNe (yellow)</td>
<td>594</td>
<td>1.4-1000</td>
<td>Water Vapor</td>
<td>118</td>
</tr>
<tr>
<td>610</td>
<td>HeNe (orange)</td>
<td>610</td>
<td>1.4-1000</td>
<td>Hydrogen cyanide</td>
<td>337</td>
</tr>
</tbody>
</table>
Laser Emission Characteristics

- Emission Durations
  - Single pulses as short as 10 femtoseconds ($10^{-14}$ seconds)
  - Continuous wave (CW)
  - Repetitive pulses - Pulse repetition frequencies (single pulse to $10^8$ pps)
- Emission Wavelengths
  - Near ultraviolet to the far infrared
  - Usually highly monochromatic (single wavelength or color)
- Beam Divergence
  - Small beam divergence (0.1 - 1 milliradian)
  - 0.5 mr divergence - 50 cm beam diameter at 1 km
  - Retinal Hazard Region: retinal irradiance diameter can be 30 micrometers or slightly less
  - Most applications use a focused beam
Update of Exposure Limits
Laser Radiation Issues

• dependence of the injury threshold on retinal irradiance diameter
• ns pulses
• near infrared exposures (wavelength dependence – new work near 1.3 µm)
• repetitive pulses
Data Sources for Updates

• Dose-response data (thresholds)
  – Animal models
  – Cell models
• Interaction or injury mechanism assessment
• Biophysical/computational models
• Medical applications
• Laser accident cases
• Environment illumination
### Laser Bioeffects

**Dose Response Relationships**

<table>
<thead>
<tr>
<th>Dose</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>Ophthalmoscopy</td>
</tr>
<tr>
<td>Exposure Duration</td>
<td>Angiography</td>
</tr>
<tr>
<td>Radiant Exposure</td>
<td>Pathology</td>
</tr>
<tr>
<td>Irradiance diameter</td>
<td>Electrophysiology</td>
</tr>
<tr>
<td>Exposure Site</td>
<td>Visual Function</td>
</tr>
<tr>
<td>Repetitive Pulse</td>
<td>Imaging (OCT, SLO)</td>
</tr>
<tr>
<td>Exposure (Hz – MHz)</td>
<td>Cellular metrics (apoptosis)</td>
</tr>
<tr>
<td>Repeated exposure</td>
<td>genomics)</td>
</tr>
</tbody>
</table>

**Time of Observation (hours, days, years?)**
Wavelength

- Absorption
  - How effectively light is captured by a target tissue
- Transmission
  - How effectively light penetrates overlying media to reach the target tissue
Extinction coefficient vs. laser wavelength
(Mainster, Bursell; Ophthalmology 1986;93:952-8)
Laser Bioeffects

- Vitreous Hemorrhage
- Retinal Burns
- Corneal Burn
- Laser Glare
Laser Induced Retinal Bioeffects

- **Temporary Effects**
  - Glare/Dazzle effects
  - Flash effects (“after image”)

- **Prolonged - Permanent Effects**
  - Retinal “burn” (edema)
  - Sub-retinal hemorrhage
  - Vitreous hemorrhage

- **Secondary Effects**
  - Retinal hole formation
  - Scar formation
  - Nerve fiber layer alterations
Measuring Retinal Injury Threshold

- NHP eye
  - Surgical level anesthesia
  - Retrobulbar block
  - Marker lesions define grid
  - Dose varied site-to-site

- Evaluate at 1 hr, 24 hrs
  - Fundus Photography
  - Direct Ophthalmoscope
  - Response = Any detectable change
Measuring Retinal Injury Thresholds

**ED$_{50}$** – that dose having a 50% probability of producing an ophthalmoscopically observable lesion at 1 – 48 hours after exposure.

**TIE** – Total Intraocular Energy. That energy incident at the cornea of the eye within the area of the ocular pupil.
Threshold laser-induced retinal injury occurs at the RPE due to the melanin absorption
Laser-induced Retinal injury

Injury at 1 to 3 times the injury threshold (ms-duration exposure)

Injury at 20 times the injury threshold (ns-duration exposure)
LASER-INDUCED RETINAL HEMORRHAGE THRESHOLDS COMPARED TO MINIMUM VISIBLE LESION THRESHOLDS
(Exposure duration = 3.5 ns)

<table>
<thead>
<tr>
<th>λ (nm)</th>
<th>ED$_{50}$ (μJ)</th>
<th>1Hr</th>
<th>24Hr</th>
<th>Hemor.</th>
</tr>
</thead>
<tbody>
<tr>
<td>410</td>
<td>77</td>
<td>49</td>
<td>110</td>
<td></td>
</tr>
<tr>
<td>420</td>
<td>27</td>
<td>24</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>430</td>
<td>18</td>
<td>15</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>442</td>
<td>17</td>
<td>13</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>450</td>
<td>8.4</td>
<td>6.9</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>458</td>
<td>6.3</td>
<td>6.2</td>
<td>63</td>
<td></td>
</tr>
<tr>
<td>476</td>
<td>4.8</td>
<td>4.6</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>488</td>
<td>4.2</td>
<td>4.5</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>493</td>
<td>8.9</td>
<td>5.3</td>
<td>43</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>7.8</td>
<td>5.0</td>
<td>74</td>
<td></td>
</tr>
<tr>
<td>510</td>
<td>6.9</td>
<td>5.3</td>
<td>72</td>
<td></td>
</tr>
<tr>
<td>520</td>
<td>5.9</td>
<td>4.0</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>530</td>
<td>4.2</td>
<td>3.3</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>580</td>
<td>5.9</td>
<td>4.2</td>
<td>63</td>
<td></td>
</tr>
</tbody>
</table>
**Photochemical Effect**

- Photochemical lesions are delayed 24 to 48 hours
- Threshold dose in retinal radiant exposure:
  - Constant with exposure duration (reciprocity)
  - Independent of the retinal irradiance diameter
- Small temperature rise

**Thermal Effect**

- Generally observable in one hour
- Threshold dose in retinal radiant exposure:
  - Vary as $t^{3/4}$ where $t$ is the exposure duration
  - Vary as the diameter of the irradiated area (ms to sec)
- Time-Temperature history

**Photochemical and Thermal**

- “Marker lesions”: 514 nm
  - 100 msec
- Lesion array: 440 nm,
  - 100 sec
Reciprocity of Irradiance and Exposure Duration
Corneal Injury Thresholds for 350 - 360 nm Exposures for Single and Multiple Exposures (60 J/cm²)

Zuclich et al, 1998
Corneal Lesions at 1.3 μm
Lesions of the Cornea, Lens and Iris
1315 nm Laser Exposure
Rhesus retina with 1315 nm laser exposures and Argon marker burns. Note the radial streaks passing through the 1315 nm lesions directed toward the fovea.

A section of the above retina. Histologic sections on the following slide correspond to areas 1, 2, 3, & 4 indicated here.
HISTOLOGY OF RHESUS RETINA WITH 1315 nm LASER EXPOSURE
Retinal ED\textsubscript{50} Threshold Data and ELs for 0.7 to 1.4 μm Exposure Durations, 0.1 s and ns
RETINAL
Minimal Visible Lesion (ED$_{50}$) and the ICNIRP Exposure Guideline

Radiant Exposure at Cornea (J/cm$^2$)

Exposure Duration (Seconds)

- Visible
- Near IR

500 - 700 nm
1.05 µm to 1.15 µm
1.2 µm to 1.4 µm
475 nm
400 - 450 nm
400 - 700 nm

Courtesy of Ben Rockwell

Exposure Limits for Laser Radiation

Bruce E. STuck, ICNIRP
Interaction/Damage Mechanisms

Thermal – mechanical (bubble formation)

Stress Confinement

Thermal Confinement

Thermal Coagulation

Total Intraocular Energy, mJ

Exposure Duration, s

1.0E-03 1.0E-09 1.0E-06 1.0E-03 1.0E+00 1.0E+03

Bruce E. STuck, ICNIRP
Retinal Injury Thresholds

\[ \text{ED50 (J/pulse)} \]

Repetitive Pulse

\[ D = 500 \, \mu m \]

\[ \text{Coll. beam} \]

\[ n^{-1/4} \]

\[ \alpha \, (\text{mrad}) \]

\[ H (J/cm^2) \]

Spot-size Dependence

MPE - Proposed

MPE 2007
Infrared Laser Bioeffects

- A. Corneal injury thresholds for “short” pulses and water absorption
- B. Corneal lesion 10.6 μm, 100 msec
- C. Porcine skin - one hour after exposure at 10.6 μm
- D. Porcine skin - 24 hours after exposure 10.6 μm
Infrared Exposure Guidelines and Corneal and Skin Injury Thresholds

(Not corrected for irradiance diameter)

Radiant Exposure (J/cm²) vs. Exposure Duration (seconds)
Pursuit-tracking performance, eye-movement, blink response, and ocular pupil response to laser glare
Laser Glare and the Ocular Response

Dim Ambient Light 3 sec Monocular Flash

Blink Summary Table (D. Stamper et al)

<table>
<thead>
<tr>
<th>Exposure Duration (sec)</th>
<th>Ambient Luminance</th>
<th>Corneal Irradiance (mw/cm²)</th>
<th>Blink Reflex Complete Closure</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>Bright</td>
<td>1.6</td>
<td>0/9</td>
</tr>
<tr>
<td>0.1</td>
<td>Dim</td>
<td>1.6</td>
<td>2/10</td>
</tr>
<tr>
<td>1.0</td>
<td>Bright</td>
<td>0.33</td>
<td>1/9</td>
</tr>
<tr>
<td>1.0</td>
<td>Dim</td>
<td>0.33</td>
<td>1/10</td>
</tr>
<tr>
<td>3.0</td>
<td>Bright</td>
<td>0.33</td>
<td>2/9</td>
</tr>
<tr>
<td>3.0</td>
<td>Dim</td>
<td>0.33</td>
<td>0/10</td>
</tr>
</tbody>
</table>

Pupil Diameter Following 0.1, 1.0, and 3.0 Sec Laser Exposure in Dim Light

Blink Summary Table (Prof. Hans-Dieter Reidenbach et al)

<table>
<thead>
<tr>
<th>λ nm</th>
<th>Exposure Duration ms</th>
<th>TIP (mW)</th>
<th>Total number of test persons</th>
<th>Number showing a blink reflex</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>532</td>
<td>250</td>
<td>0.8</td>
<td>214</td>
<td>48</td>
<td>22.4</td>
</tr>
<tr>
<td>635</td>
<td>250</td>
<td>0.8</td>
<td>215</td>
<td>37</td>
<td>17.2</td>
</tr>
<tr>
<td>670</td>
<td>250</td>
<td>0.8</td>
<td>261</td>
<td>41</td>
<td>15.7</td>
</tr>
<tr>
<td>All λs</td>
<td>250</td>
<td>0.8</td>
<td>690</td>
<td>126</td>
<td>18.3</td>
</tr>
</tbody>
</table>

TIP = Total Intraocular Power

Exposure Limits for Laser Radiation

Bruce E. Stuck, ICNIRP
Summary

• Updated Exposure Limits for Laser Radiation.
  – Spot-size dependence (“time dependent $\alpha_{\text{max}}$”)
  – Nanosecond exposure durations
  – Repetitive pulses
  – Near Infrared
  – Measurement acceptance angles more clearly defined

• Update had a long gestation period! Basis: Data acquired and reviewed in the last 3-10 years.

• Most of the ELs have NOT changed.

• Harmonization – Based upon ICNIRP Guidelines!
Future Research/Issues

- Long duration exposures
  - Advanced imaging devices
- Repetitive pulses
- Far Infrared - 10 μm to 1 mm (THz region)
Acknowledgements

• Jack Lund
• Brian Lund
• Karl Schulmeister
• Per Soderberg
• David Sliney
• Benjamin Rockwell
• Robert Thomas
• Jeremiah Brown, Jr.
• Martin Mainster
• Joseph A. Zuclich
Thank you!

Questions?