Exposure Limits for Laser Radiation

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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 keratomilieusis)
  - Photocoagulation
  - Photodisruption (secondary cataract removal)
  - Photodynamic therapy (PDT)
  - Surgery - endoscope compatible
  - Biostimulation or biomodulation
  - Flourescence angiography
  - Imaging (SLO, Wavefront corrected retinal Imaging, OCT)
  - Alignment (MRI)
  - Doppler blood flow
  - Skin rejuvenation (fractional laser therapy)

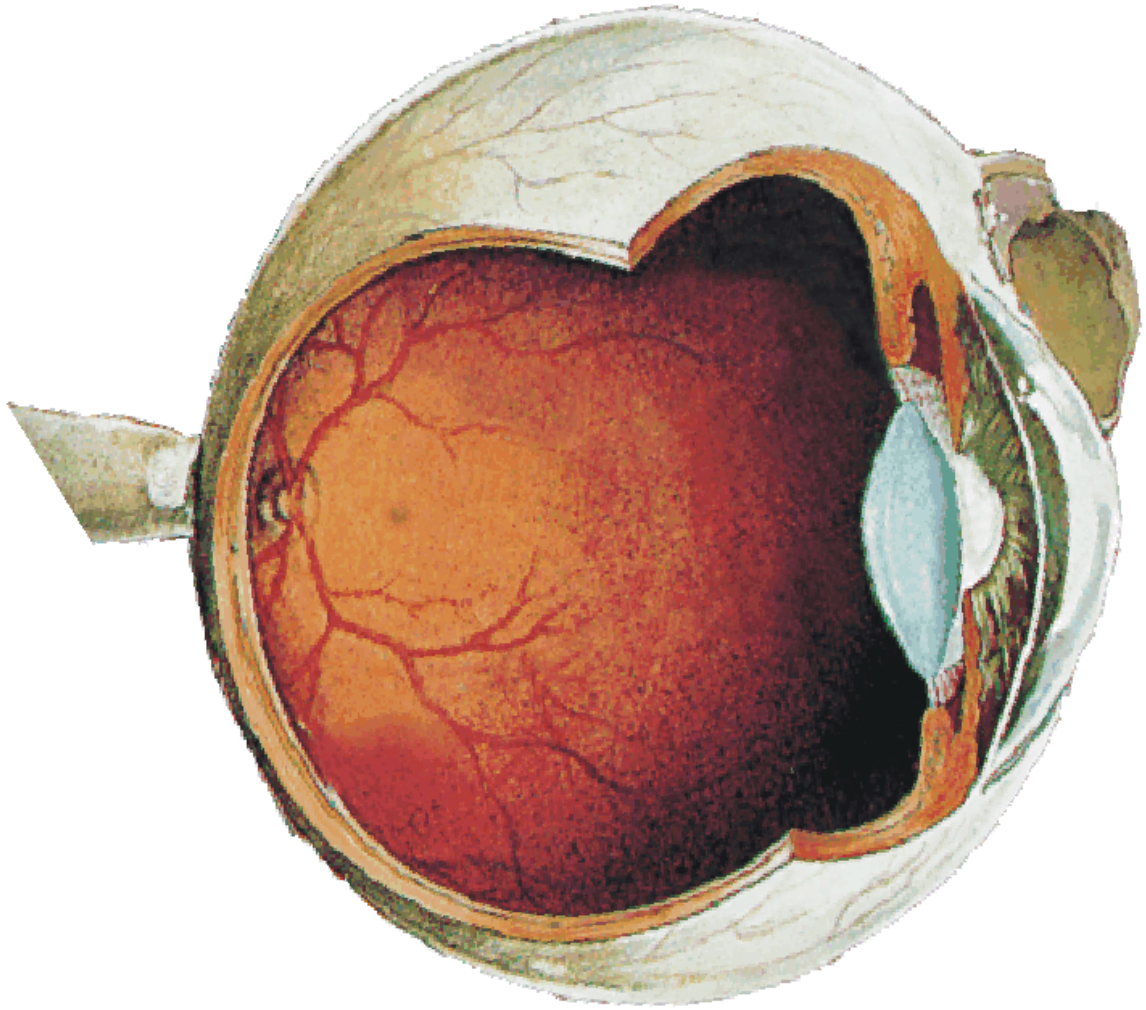
Common Lasers and Laser Wavelengths

Wavelength Range (nm)	Laser Type	Wavelength(s) (nm)
Ultraviolet 180-315	ArF Excimer	193
	KrCl Excimer	222
	KrF Excimer	248
	Nd:YAG(quadrupled)	266
	Argon	275
	XeCl Excimer	308
315-400	Helium Cadmium	325
	Nitrogen	337
	XeF Excimer	351
	Argon	351, 363
	Krypton	350.7, 356.4
Visible 400-700	Helium Cadmium	441.6
	Argon	476, 488, 514.5
	Copper Vapor	511, 568
	Krypton	530
	Nd:YAG (doubled)	532
	Helium Neon(HeNe)	543
	Dye (Coumarin)	400-550
	Dye (Rhodamine)	550-700
	HeNe (yellow)	594
	HeNe (orange)	610

Wavelength Range (um)	Laser Type	Wavelength(s) (um)
	HeNe (red)	632.8
	InGaAlP	670nm
	Krypton	647-676 nm
	Ruby	694.3 nm
Near Infrared 0.7-1.4	Ti:Sapphire	0.7-1.0
	GaAlAs	0.78
	Alexandrite	0.72-0.80
	GaAlAS	0.85
	GaAs	0.905
	Nd:Glass	1.060
	Nd:YAG	1.064
	(HeNe)	1.080, 1.156
	Nd:YAG	1.318, 1.338, 1.356
Infrared 1.4-1000	Erbium Glass	1.54
	Holmium	2.06
	Hydrogen Flouride	2.6-3.0
	Erbium YLF	2.94
	Deuterium Flouride	3.8-4.0
	Carbon Monoxide	5.0-5.5
	Carbon Dioxide	10.6
	Water Vapor	118
	Hydrogen cyanide	337

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

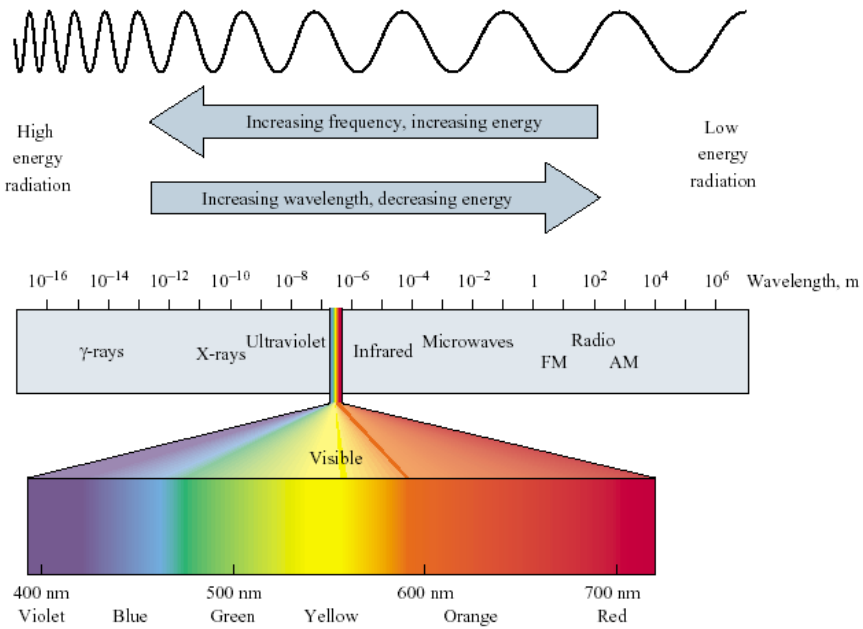
Laser Bioeffects

Dose Response Relationships

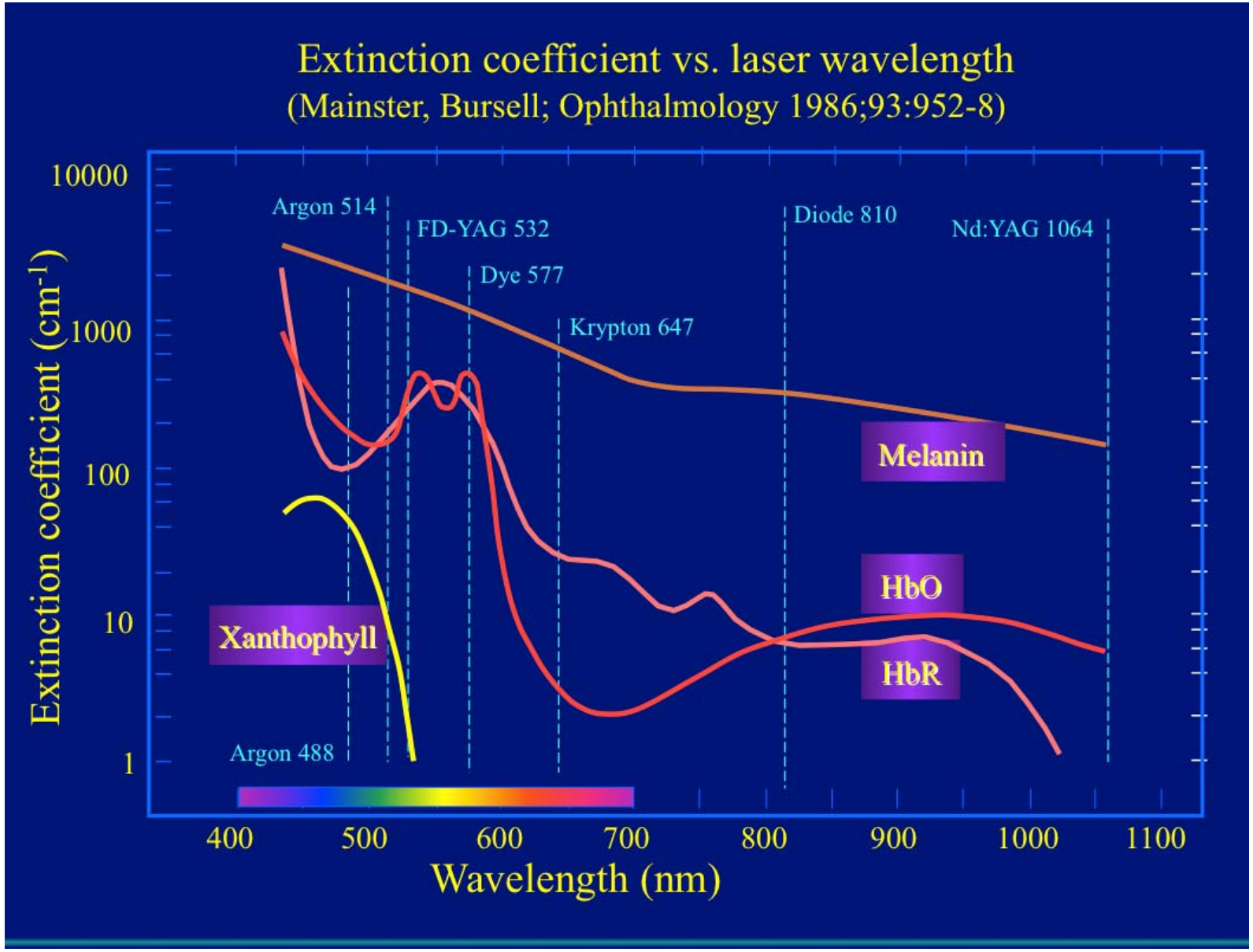
Dose	Response
Wavelength	Ophthalmoscopy
Exposure Duration	Angiography
Radiant Exposure	Pathology
Irradiance diameter	Electrophysiology
Exposure Site	Visual Function
Repetitive Pulse	Imaging (OCT,SLO)
Exposure (Hz – MHz)	Cellular metrics (apoptosis)
Repeated exposure	genomics)

Time of Observation (hours, days, years?)

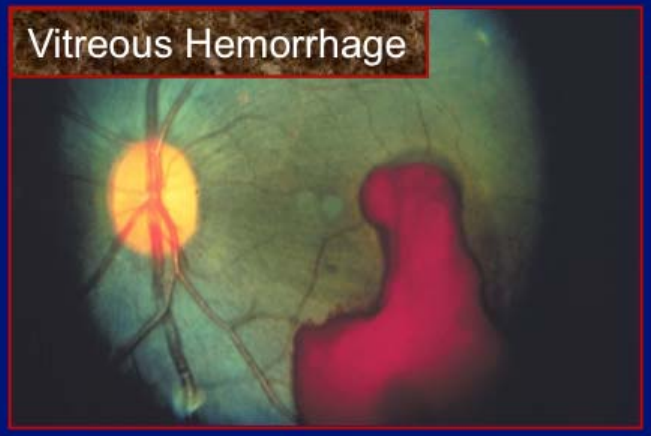
Wavelength

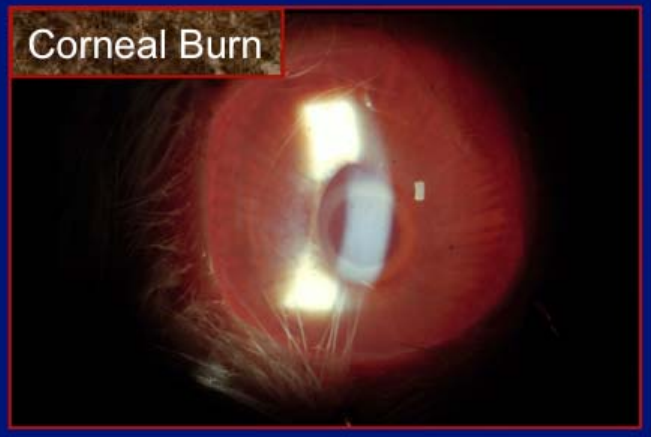


- Absorption
  - How effectively light is captured by a target tissue
- Transmission
  - How effectively light penetrates overlying media to reach the target tissue


Extinction coefficient vs. laser wavelength
(Mainster, Bursell; Ophthalmology 1986;93:952-8)
Extinction coefficient (cm-1)
10000
1000
100
10
1
Argon 514
FD-YAG 532
Dye 577
Krypton 647
Diode 810
Nd:YAG 1064
Melanin
HbO
HbR
Xanthophyll
Argon 488
400
500
600
700
800
900
1000
1100
Wavelength (nm)

Laser Bioeffects

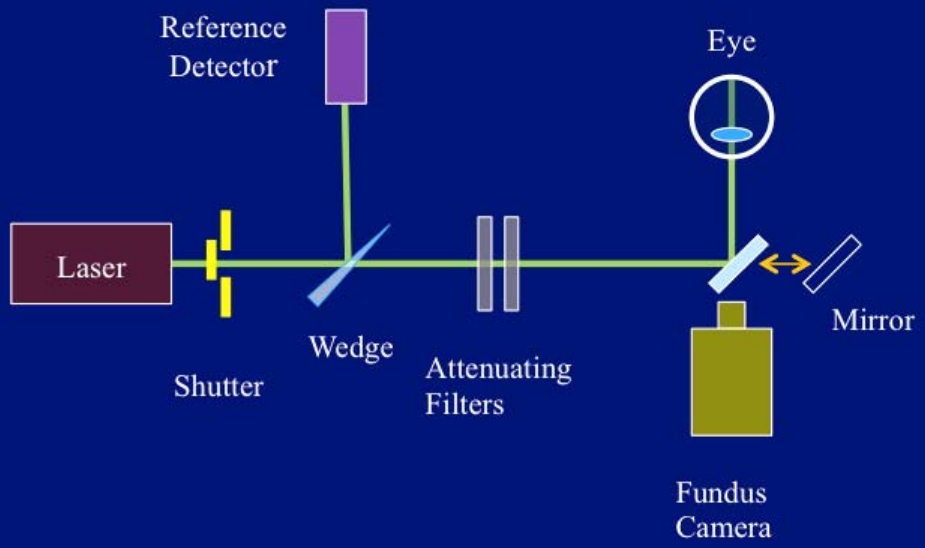




Laser Induced Retinal Bioeffects

- 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

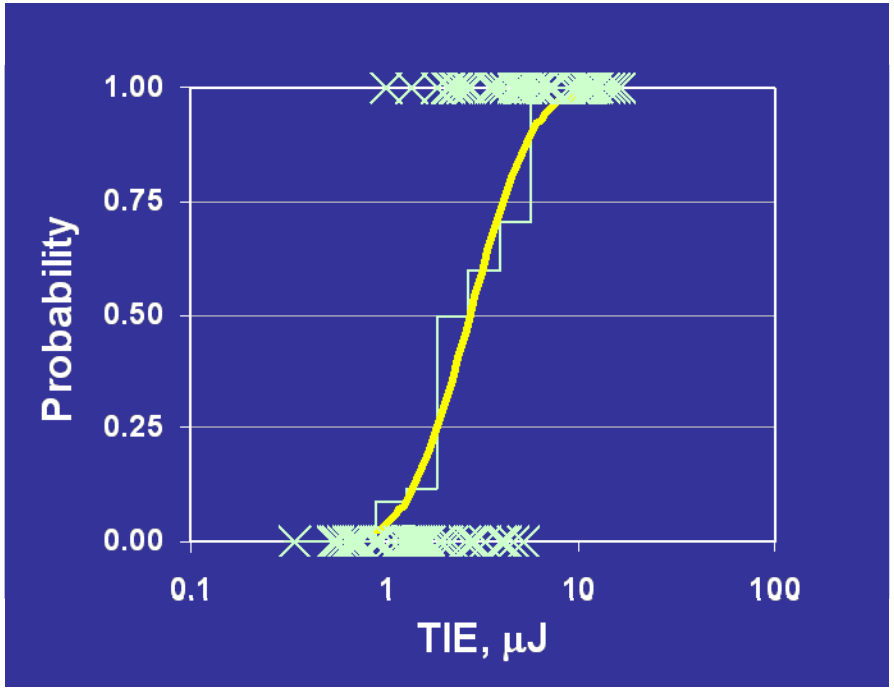
Measuring Retinal Injury Threshold



- 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

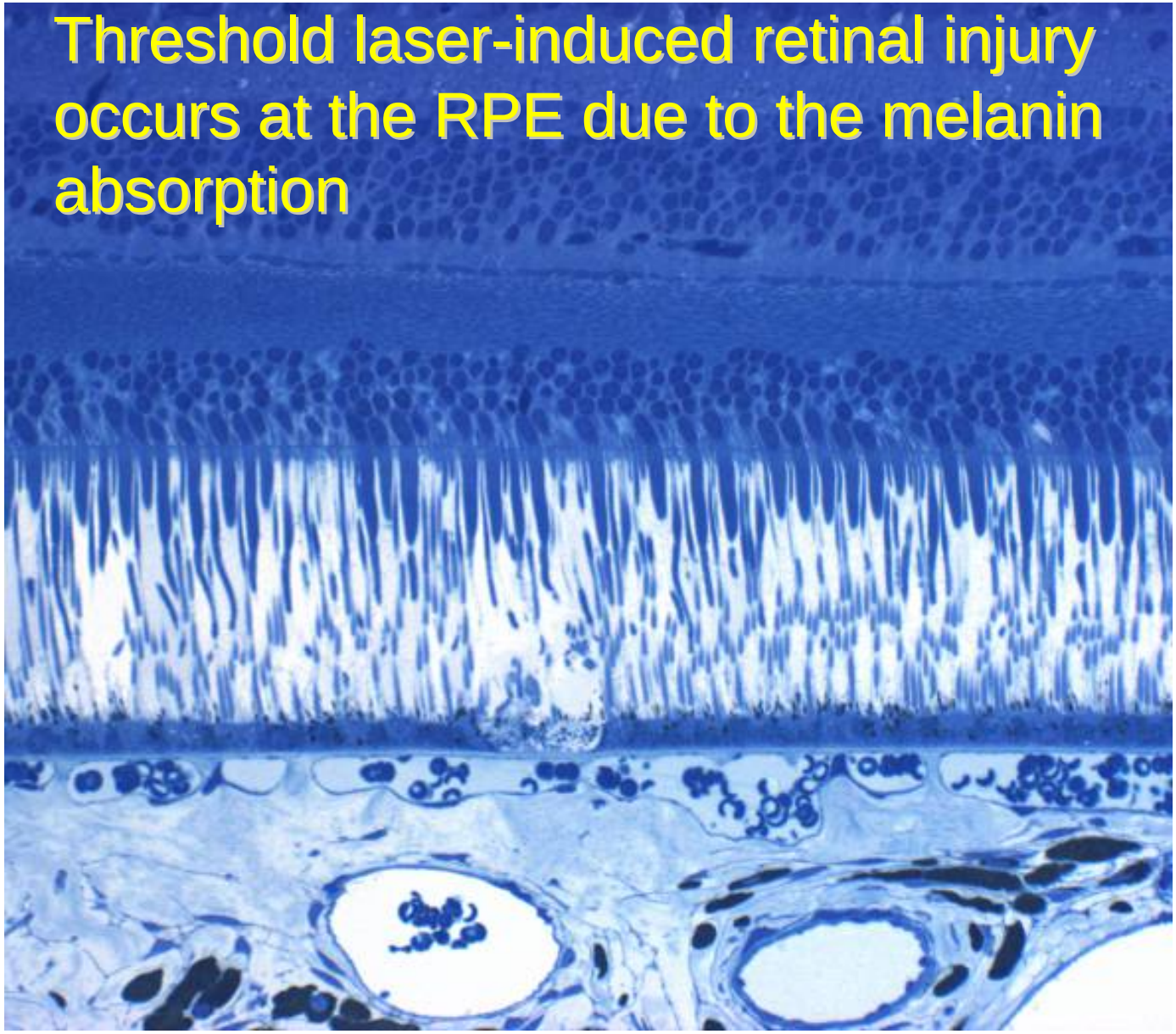
Measuring Retinal Injury Thresholds



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

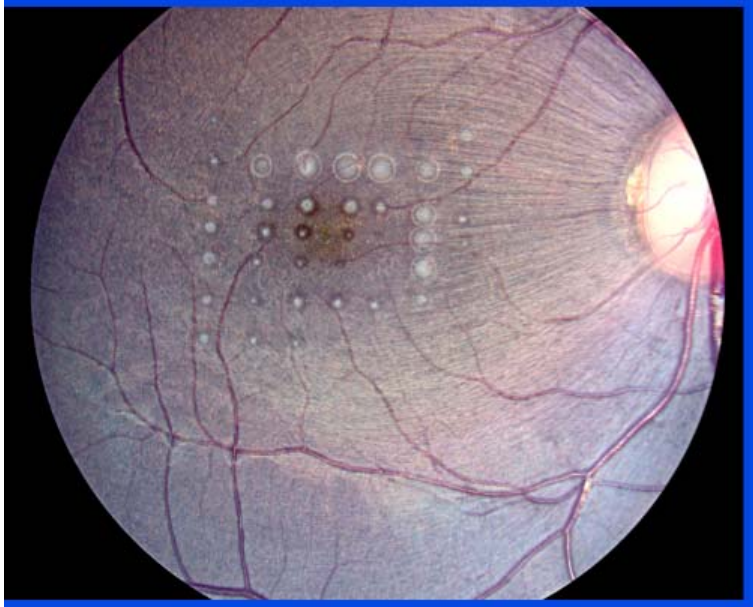
TIE – Total Intraocular Energy. That energy incident at the cornea of the eye within the area of the ocular pupil

Threshold laser-induced retinal injury occurs at the RPE due to the melanin absorption

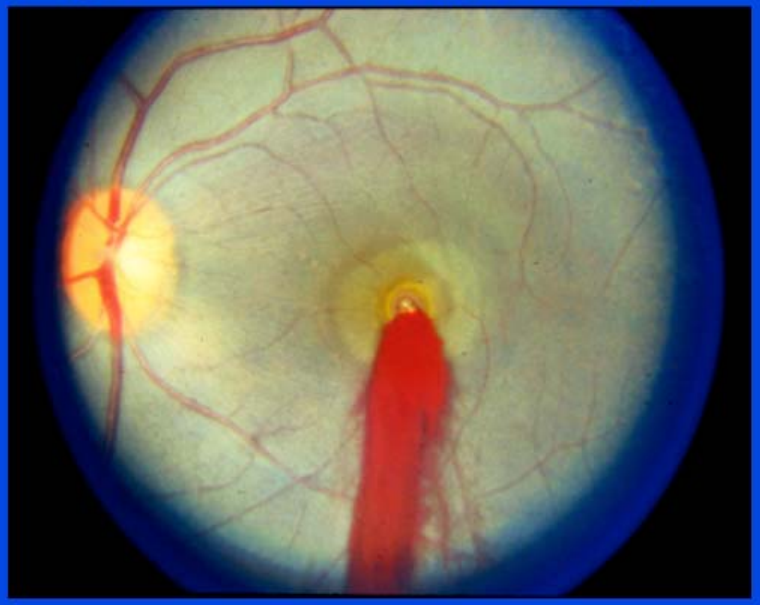


Laser-induced Retinal injury

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



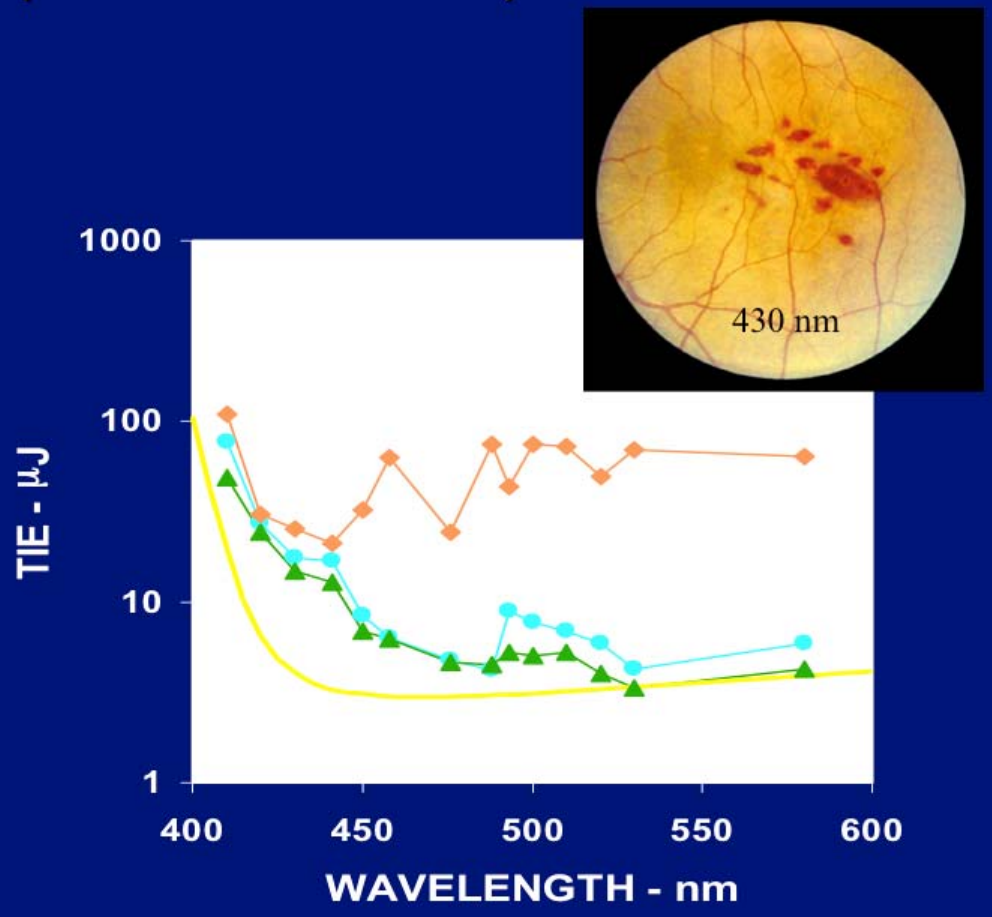
Injury at 20 times the injury threshold (ns-duration exposure)



LASER-INDUCED RETINAL HEMORRHAGE THRESHOLDS COMPARED TO MINIMUM VISIBLE LESION THRESHOLDS

(Exposure duration = 3.5 ns)

	ED_{50}- µJ		
λ	1Hr	24Hr	Hemor.
410	77	49	110
420	27	24	31
430	18	15	27
442	17	13	21
450	8.4	6.9	32
458	6.3	6.2	63
476	4.8	4.6	28
488	4.2	4.5	75
493	8.9	5.3	43
500	7.8	5.0	74
510	6.9	5.3	72
520	5.9	4.0	50
530	4.2	3.3	70
580	5.9	4.2	63

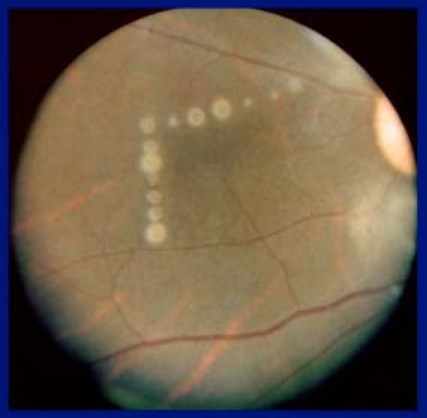


Photochemical Effect

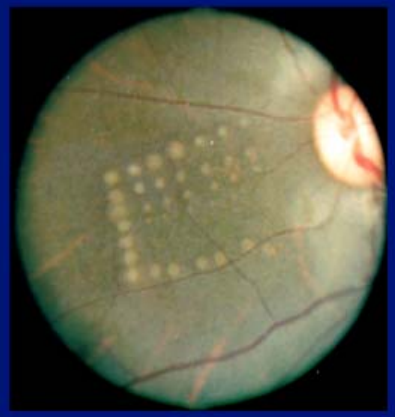
- Photochemical lesions are delayed 24 to 48 hours
- Threshold dose in retinal radiant exposure:
  - Constant with exposure duration (reciprocity)
  - Independent of the retinal irradiance diameter
- Small temperature rise

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



1 hour after exposure



48 hours after exposure

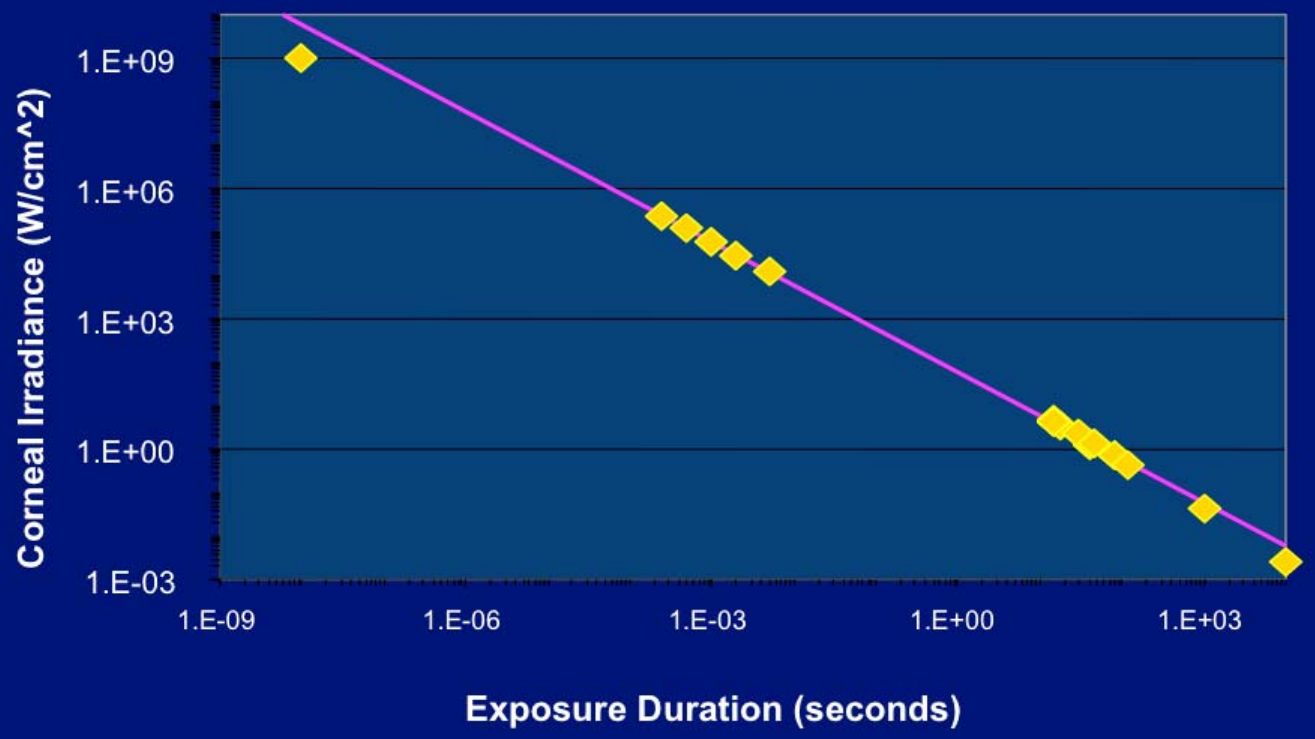
Photochemical and Thermal

"Marker lesions": 514 nm
100 msec

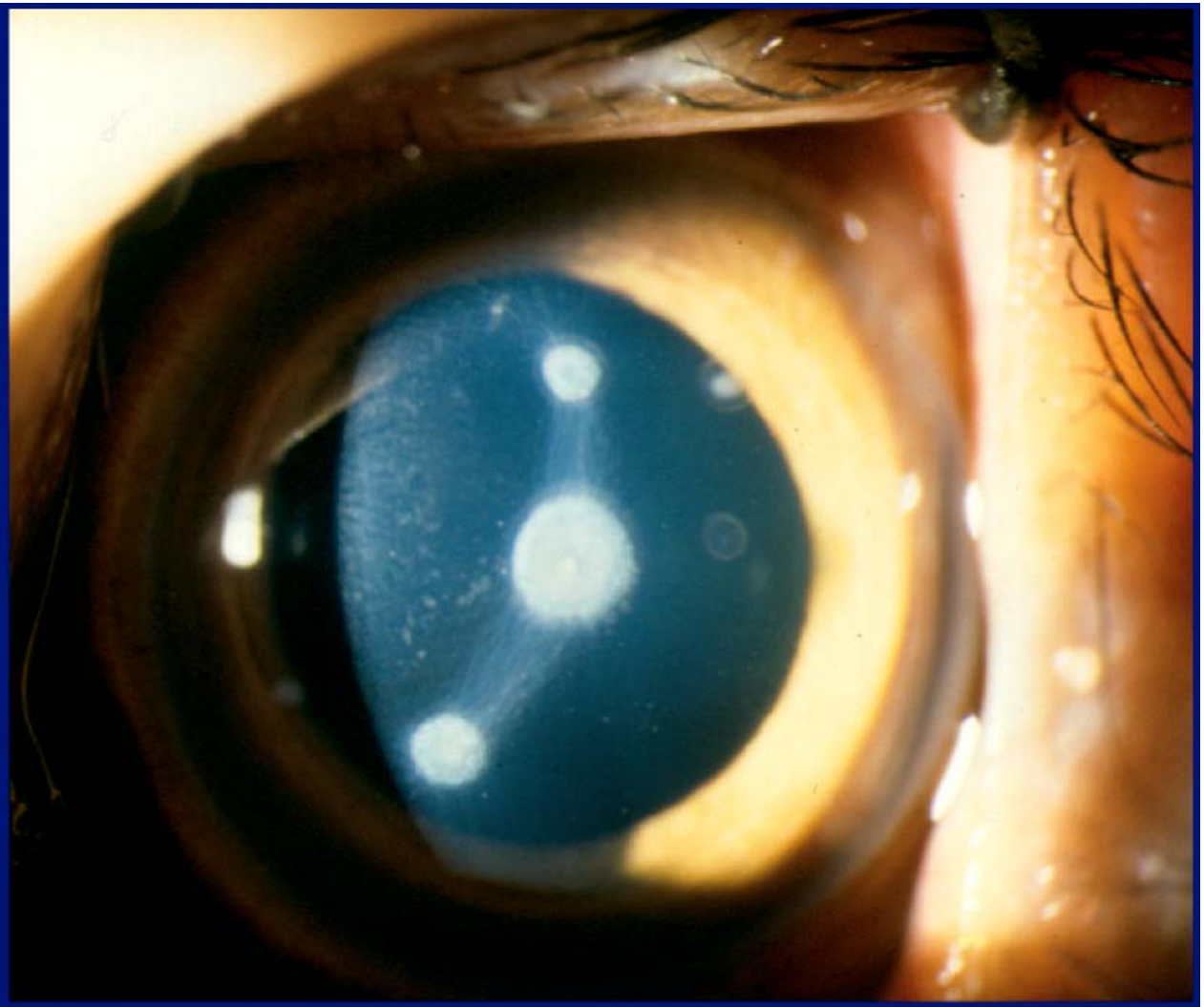
Lesion array: 440 nm,
100 sec

Reciprocity of Irradiance and Exposure Duration

Corneal Injury Thresholds for 350 -360 nm Exposures for Single and Multiple Exposures (60 J/cm^2)

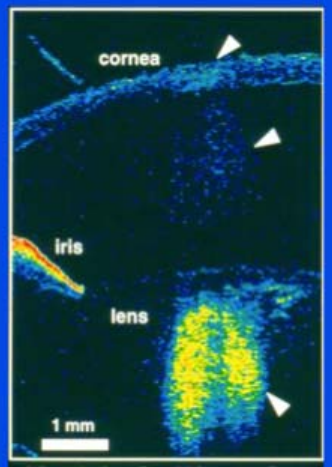


Zuclich et al, 1998

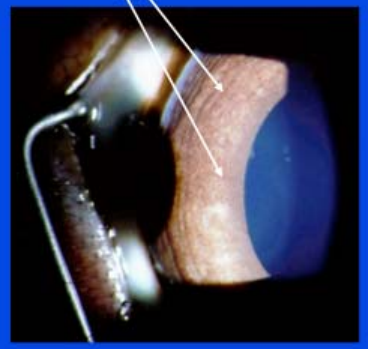


Corneal Lesions at 1.3 μm

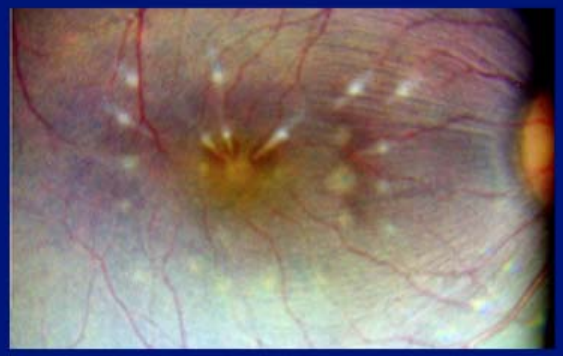
Lesions of the Cornea, Lens and Iris
1315 nm Laser Exposure

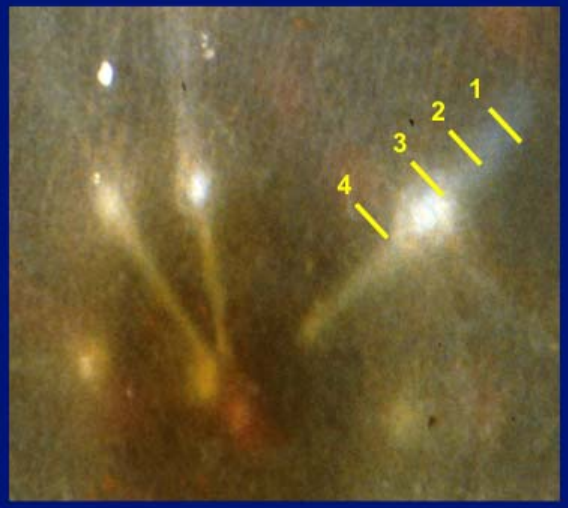


1.3 µm lesions in rabbit cornea/lens

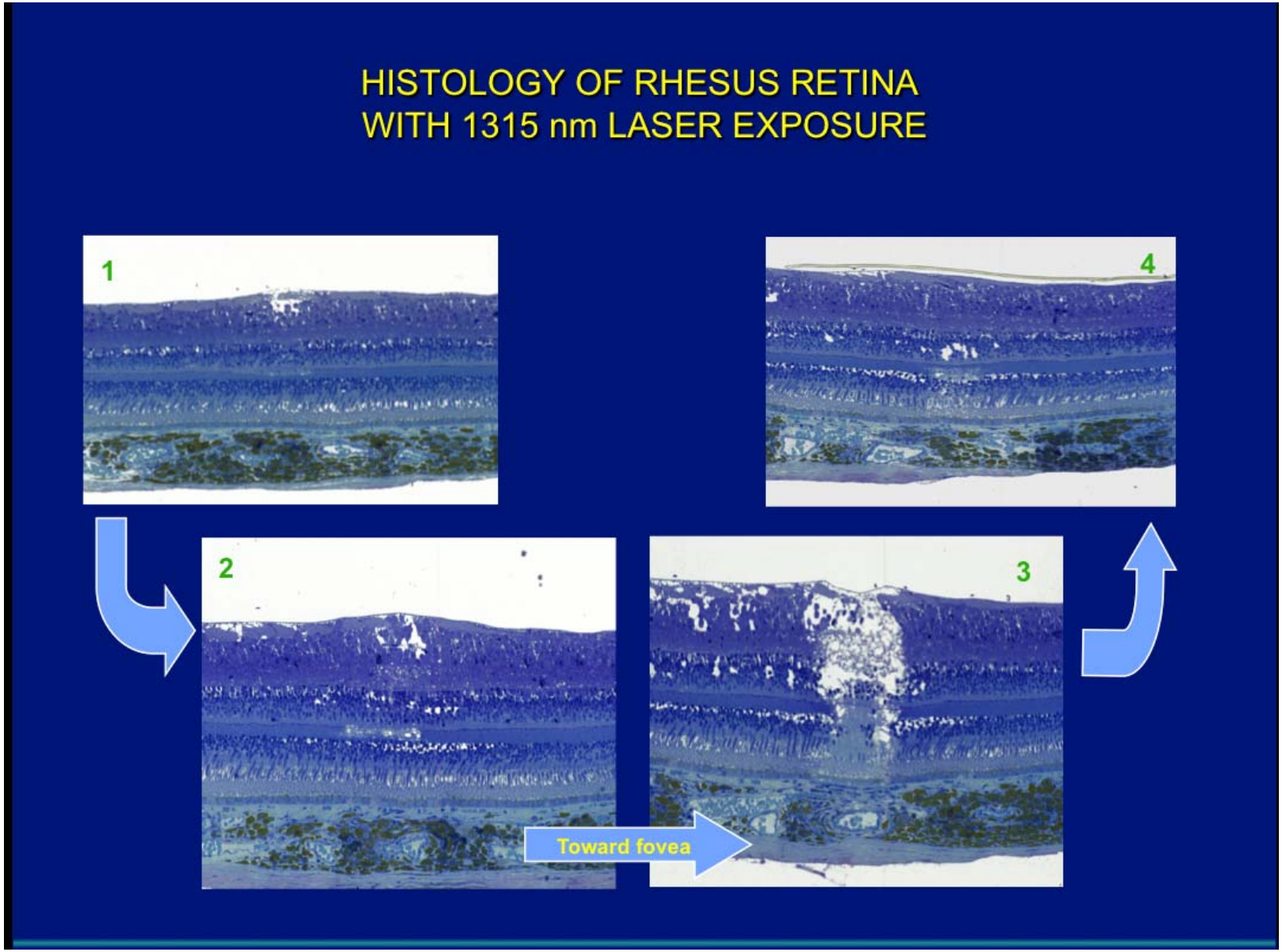


RHESUS RETINA WITH 1315 nm LASER EXPOSURES

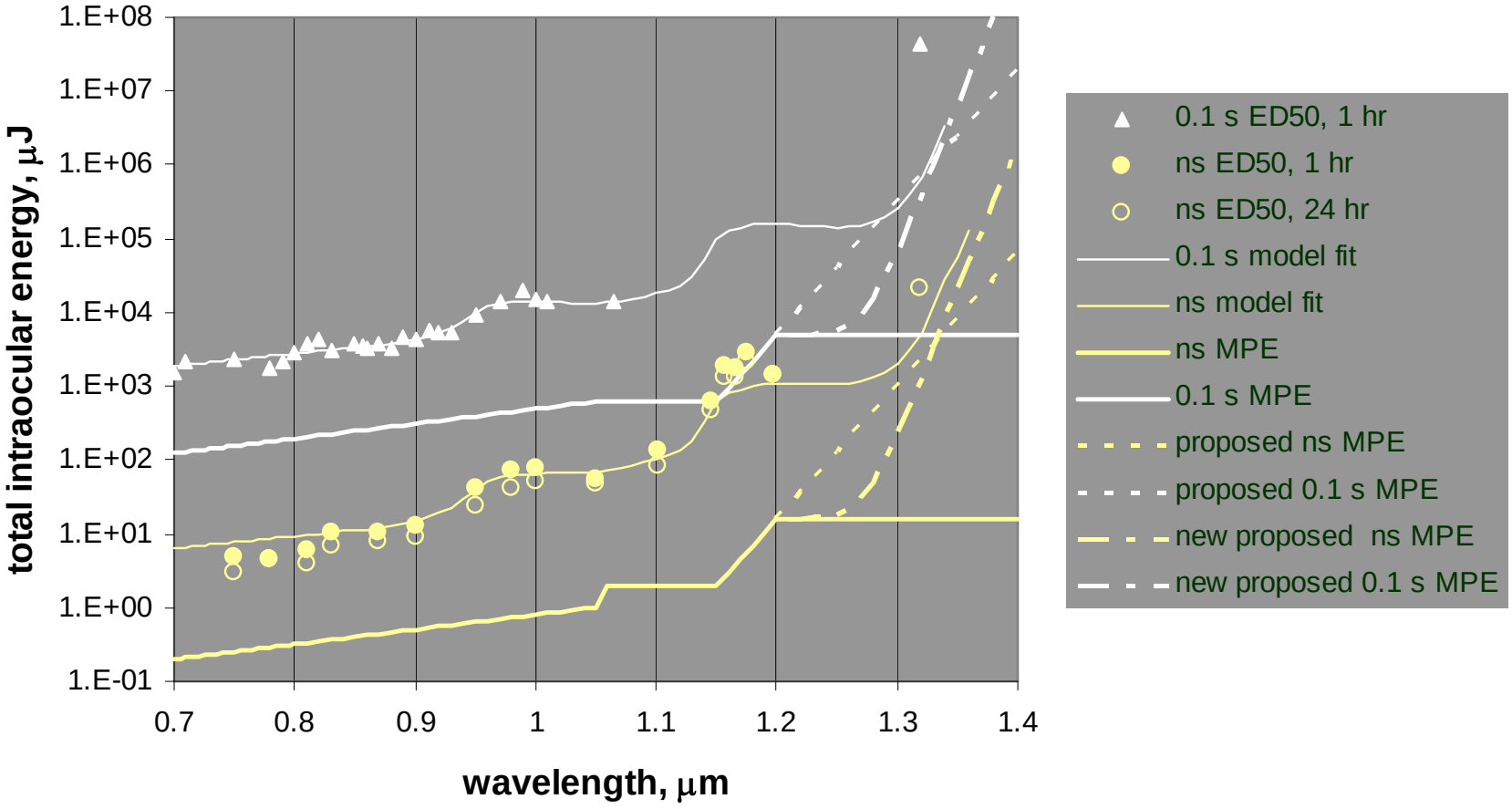


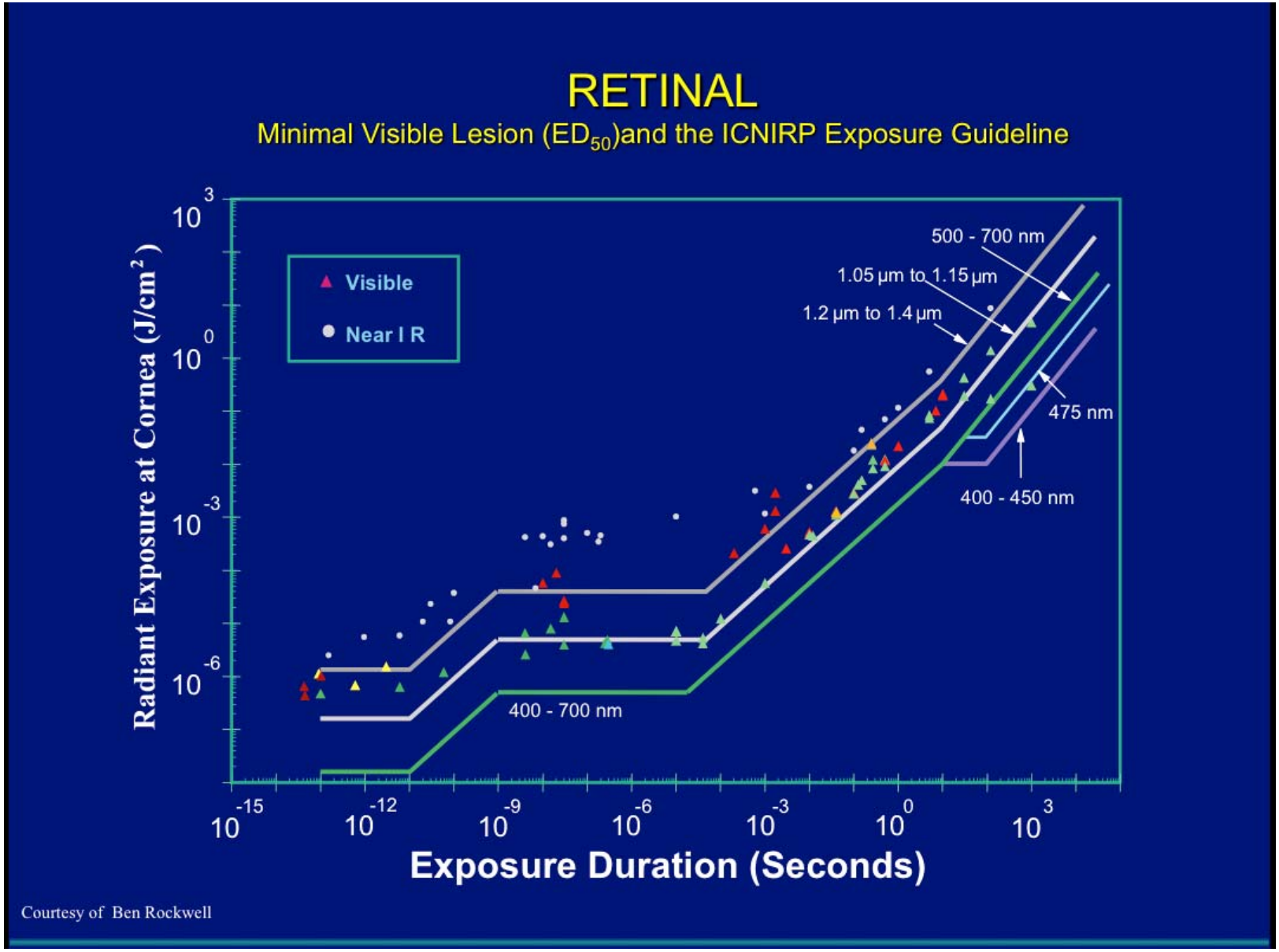


- Rhesus retina with I315 nm laser exposures and Argon marker burns. Note the radial streaks passing through the 1315 nm lesions directed toward the fovea.
- A section of the above retina. Histologic sections on the following slide correspond to areas 1, 2, 3, & 4 indicated here.

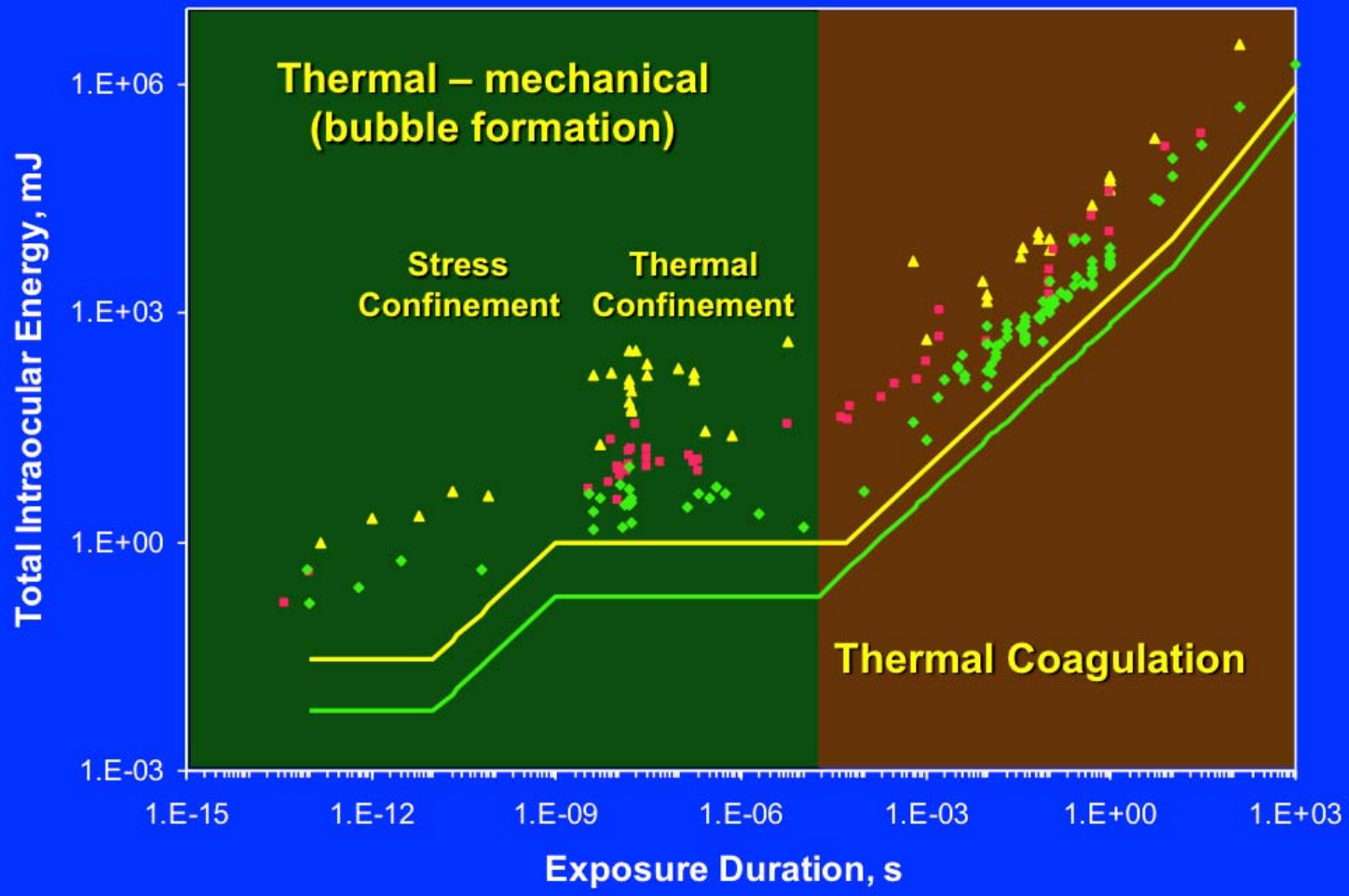

HISTOLOGY OF RHESUS RETINA
WITH 1315 nm LASER EXPOSURE
1
2
3
4
Toward fovea

Retinal ED_{50} Threshold Data and ELs for 0.7 to 1.4 μm Exposure Durations, 0.1 s and ns

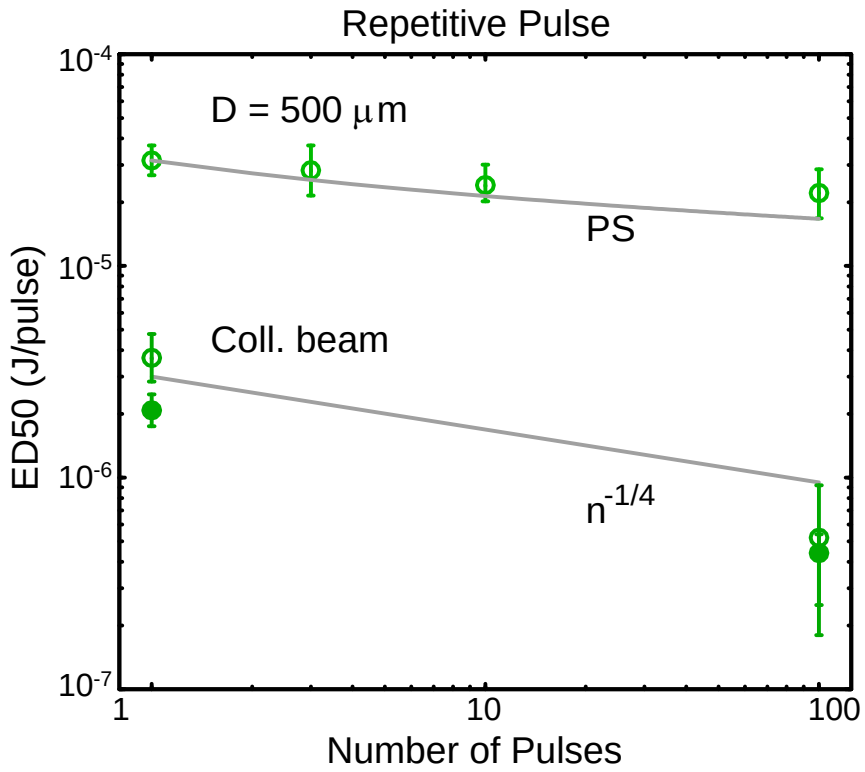


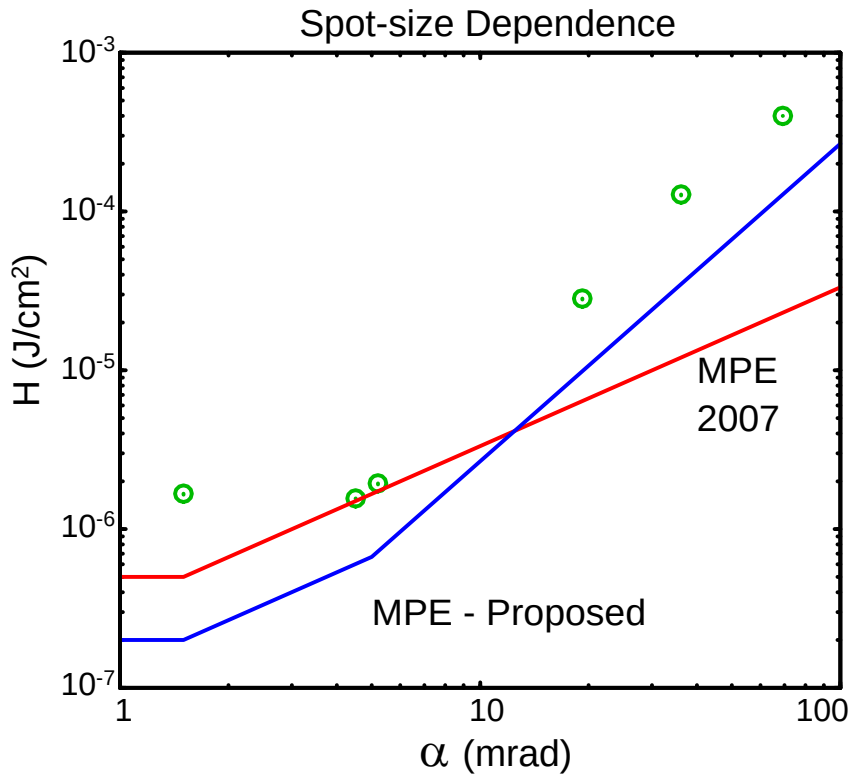

RETINAL
Minimal Visible Lesion (ED_{50})and the ICNIRP Exposure Guideline
Visible
Near I R
500 - 700 nm
1.05 µm to 1.15 µm
1.2 µm to 1.4 µm
475 nm
400 - 450 nm
400 - 700 nm
Radiant Exposure at Cornea (J/cm²)
10^{3}
10^{0}
10^{-3}
10^{-6}
10^{-15}
10^{-12}
10^{-9}
10^{-6}
10^{-3}
10^{0}
10^{3}
Exposure Duration (Seconds)
Courtesy of Ben Rockwell

Interaction/Damage Mechanisms



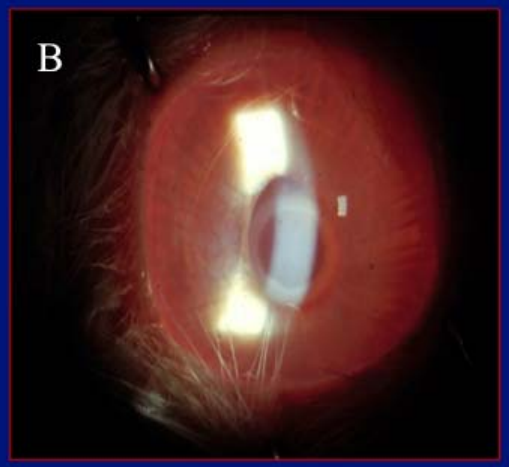
Retinal Injury Thresholds

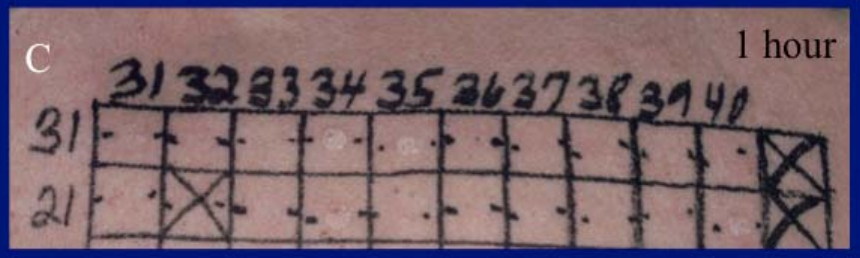


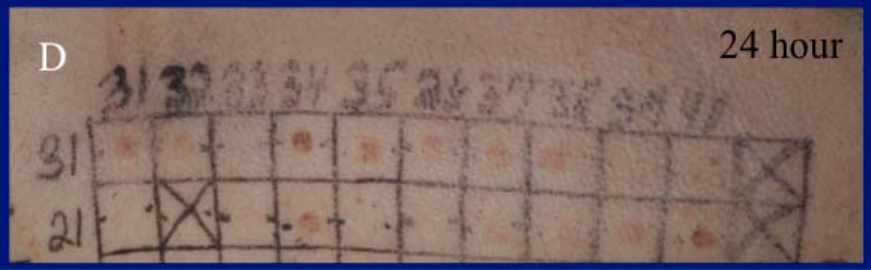


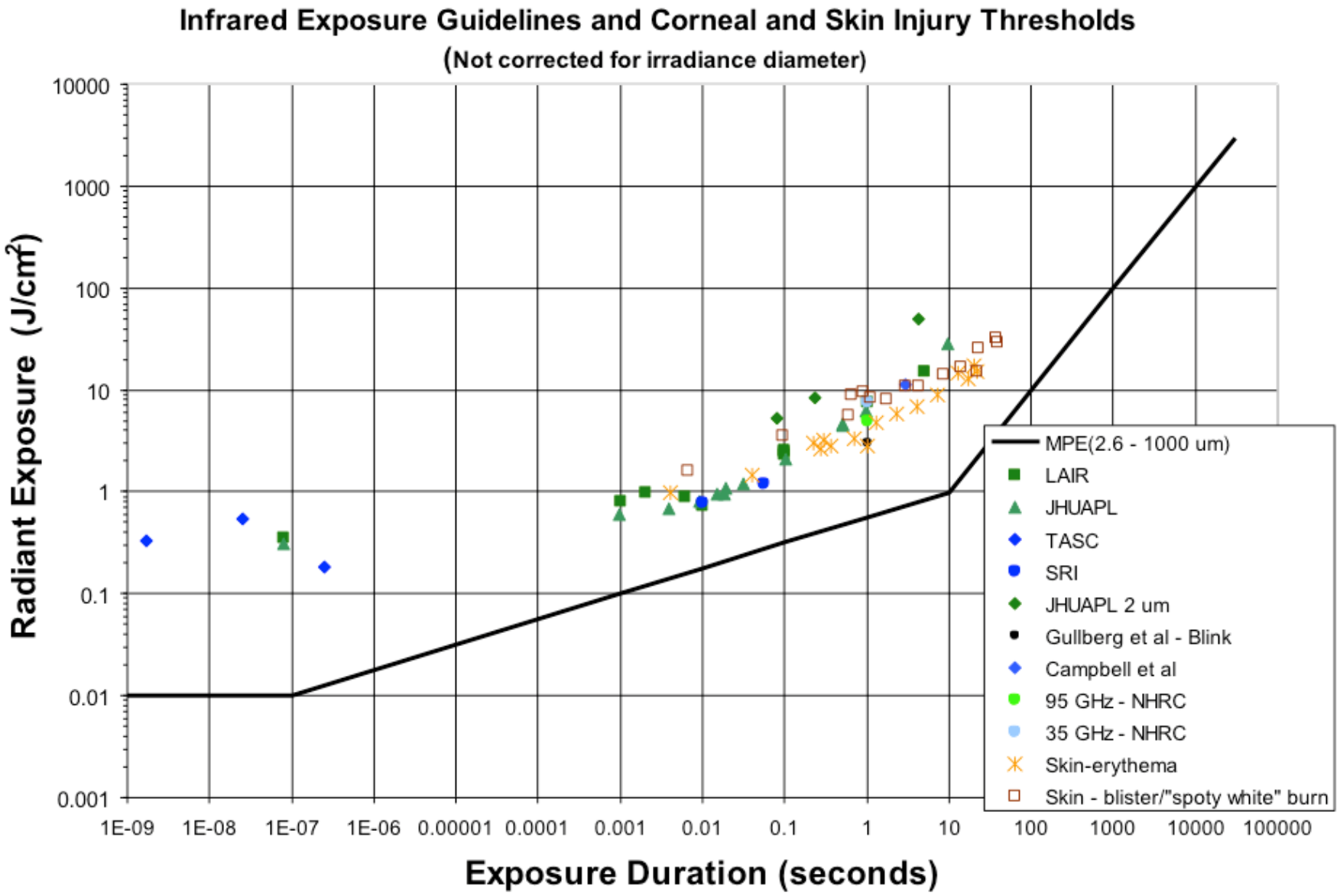
Infrared Laser Bioeffects

- 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

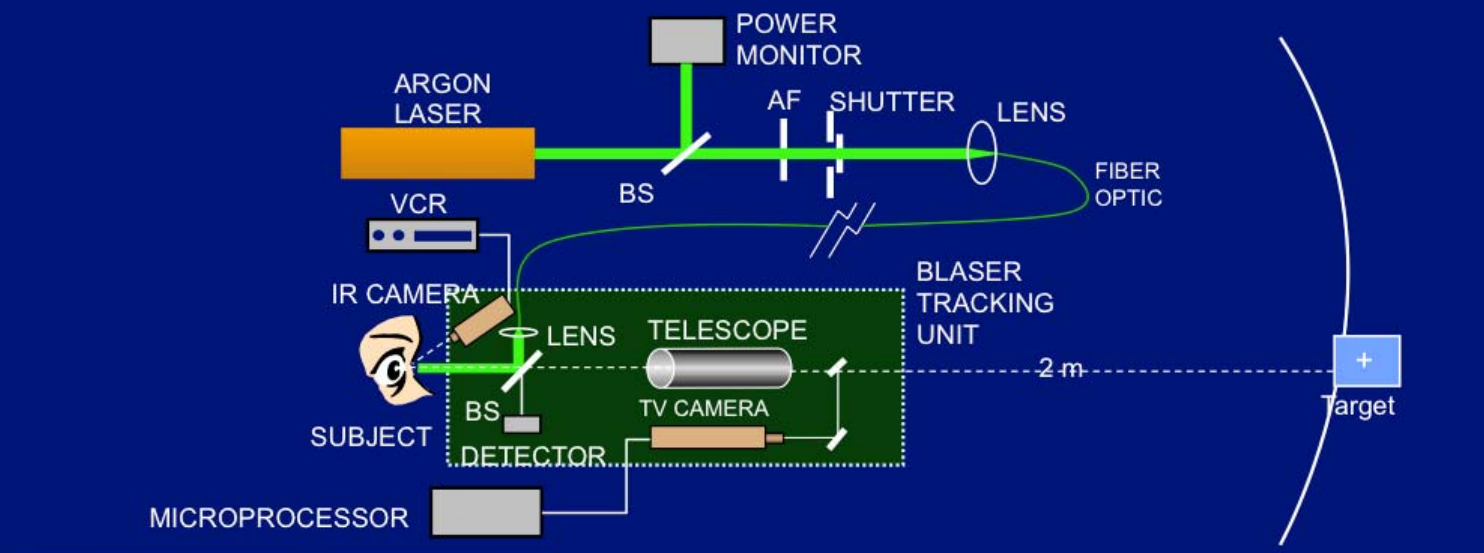


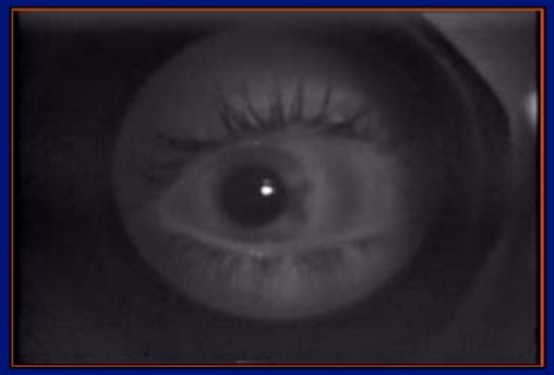


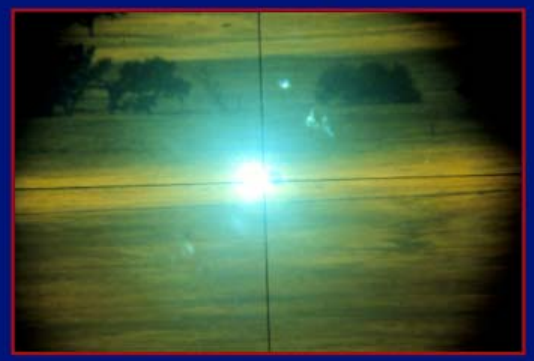



Infrared Exposure Guidelines and Corneal and Skin Injury Thresholds
(Not corrected for irradiance diameter)
Radiant Exposure (J/cm²)
10000
1000
100
10
1
0.1
0.01
0.001
1E-09
1E-08
1E-07
1E-06
0.00001
0.0001
0.001
0.01
0.1
1
10
100
1000
10000
100000
Exposure Duration (seconds)
MPE(2.6 - 1000 um)
LAIR
JHUAPL
TASC
SRI
JHUAPL 2 um
Gullberg et al - Blink
Campbell et al
95 GHz - NHRC
35 GHz - NHRC
Skin-erythema
Skin - blister/"spoty white" burn

Pursuit-tracking performance, eye-movement, blink response, and ocular pupil response to laser glare



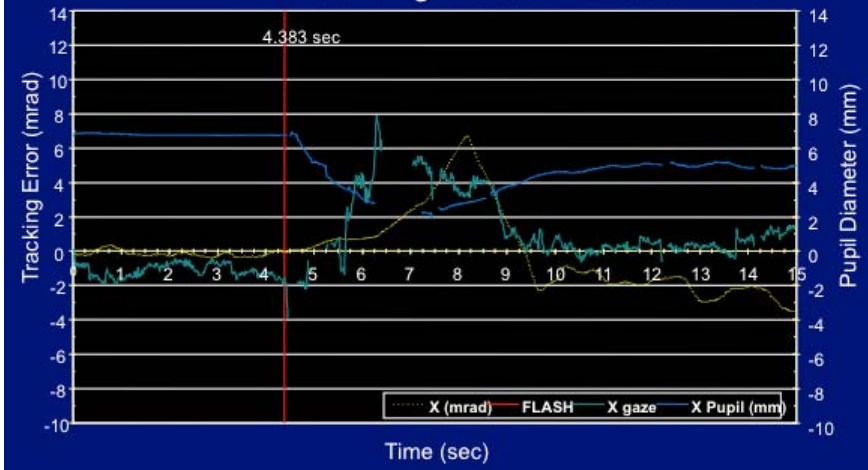




D.A. S[illegible] et al, Perceptual and Motor Skills, 2002

Laser Glare and the Ocular Response

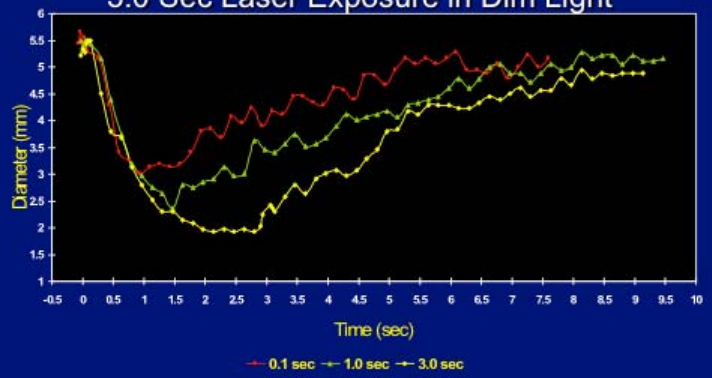
Dim Ambient Light 3 sec Monocular Flash



Blink Summary Table (D. Stamper et al)

Exposure Duration (sec)	Ambient Luminance	Corneal Irradiance mw/cm2	Blink Reflex Complete Closure
0.1	Bright	1.6	0/9
0.1	Dim	1.6	2/10
1.0	Bright	0.33	1/9
1.0	Dim	0.33	1/10
3.0	Bright	0.33	2/9
3.0	Dim	0.33	0/10

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)

λ nm	Exposure Duration ms	TIP mW	Total number of test persons	Number showing a blink reflex	Percent %
532	250	0.8	214	48	22.4
635	250	0.8	215	37	17.2
670	250	0.8	261	41	15.7
All λs	250	0.8	690	126	18.3

TIP = Total Intraocular Power

A. Stuck et al, Perceptual and Motor Skills, 2002

Summary

- Updated Exposure Limits for Laser Radiation.
  - Spot-size dependence ("time dependent α_{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 ICNRIP Guidelines!

Future Research/ Issues

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

Acknowledgements

- Jack Lund
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- Martin Mainster
- Joseph A. Zuclich

Thank you!

Questions?