Environmental Vision (OPT 6051)
Laser Safety

ELECTROMAGNETIC RADIATION

Electromagnetic radiation is energy in transit. In contrast to sound, which requires a medium through which to propagate, electromagnetic radiation can traverse empty space as well as a medium such as air or water. Different parts of the electromagnetic spectrum are identified with a particular wavelength. Out of the entire electromagnetic spectrum emitted by the sun, only two narrow bands, known as the **radio window** and **optical window**, penetrate the atmosphere and reach the earth. We are most interested in the optical window because it includes visible light, ultraviolet (UV) and infrared (IR) radiation. *Although they are invisible to the human eye, UV and IR radiation are important in clinical optometry because of their interactions with ocular tissues.*

Table 1. UV, visible and IR electromagnetic radiation.

Wavelength (nm)	*Description/name*	*Primary ocular absorption*
200-290	UV-C	cornea
290-320	UV-B	cornea
320-380	UV-A	cornea, lens
380-700	visible light	trabecular meshwork, iris, retina, choroid
400	violet	
470	blue	
540	green	
570	yellow	
600	orange	
630	red	
760-1400	IR-A	lens
1400-3,000	IR-B	lens
3,000-1,000,000	IR-C	cornea

Table 1 identifies the wavelengths associated with electromagnetic magnetic radiation in the optical window. The sun is the source of most electromagnetic radiation, but we also encounter manmade sources, such as electric lights or lasers. One band of ultraviolet radiation, UV-C, is also emitted from the sun, but it is completely absorbed by the atmosphere and does not reach the earth. The eye can, however be exposed to UV-C from manmade sources such as welding arcs, or certain lasers. Since shorter-wavelength radiation contains higher energy per photon, *shorter wavelengths cause greater damage to ocular tissues*. Radiation outside the optical window, such as x-rays (shorter wavelength than UV) or microwaves (longer wavelength than IR), can also damage ocular tissues, and these may be a hazard to workers in certain occupations.

Radiometry is the measurement of electromagnetic energy, while **photometry** is the measurement of visible light weighed by its perceived brightness to the human eye. In Vision Science II we studied photometry rather than radiometry, since we were primarily interested in perception. But when studying laser-tissue interactions, we are not interested in perceived brightness, but rather the effects of energy absorbed. Therefore, for laser safety calculations we use radiometric units such as Joules or Watts. The basic radiometric units are summarized in Table 2.

Table 2. Radiometric units.

Quantity	*Unit*	*Description*
radiant energy	joule (J)	energy
radiant power	watts (W)	energy per unit time; W = J/sec
radiant intensity	W/steradian	power **emitttted** from a **point source** contained within a unit solid angle
radiance	W/steradian/cm^2	radiant intensity **emitted** per projected area emitted by an **extended source**
irradiance	W/cm^2	radiant power falling on a surface

Most commonly used lasers produce energy far below 1 Joule, so we usually work with laser energy expressed in millijoules (mJ) or laser power expressed in milliwatts (mW). Laser safety guidelines specify safe exposure limits for the eye in terms of J/cm^2, which is closely related to irradiance in W/cm^2.

LASER EFFECTS ON OCULAR TISSUES

In comparison to a typical household light bulb, the power of most lasers is miniscule. For example, the total power output of a common 10 mW laboratory laser is 6000 times smaller than the output of a 60 W household light bulb. Yet we know that lasers are more hazardous than light bulbs.

Q. How can such a low power be hazardous?
A. Because of the unique properties of laser light, the energy is highly concentrated. This is possible because laser beams are:

- coherent (all waves travel in phase, all of the same wavelength)
- highly collimated (parallel with little beam expansion over distance)

Lasers used in clinical eye care transfer energy to ocular tissues, which absorb the energy and produce one of the following tissue effects:

- **photoablation**
- **photocoagulation**
- **photodisruption**

Figure 1. The VISX Star S4 laser, which is used for LASIK and PRK. It can be integrated with the VISX WaveScan aberrometer.

a. **Photoablation**. High energy radiation instantaneously destroys molecular bonds, and tissue is vaporized. *The effect is highly localized*; that is, while one molecule is destroyed, the neighboring molecule is untouched. This permits very precise sculpting of tissues. An example of photoablation is the use of the ***excimer laser*** *(193-nm UV) in LASIK and PRK* (Fig. 1). Laser eye surgeons point out that a

single excimer laser pulse removes about 0.25 μm of tissue, which is an indication of its potential accuracy (see Fig. 2). This however, is no indication of how well the procedure will correct a patient's vision. The surgeon needs, not only a precise scalpel to make the cut (the laser), but he must also know where and how much to cut. Aberrometers such as the VISX WaveScan can provide refractive surgeons with the detailed optical data needed to take advantage of the precision offered by the excimer laser. Wavefront-guided refractive surgery is producing better optical and visual results than conventional laser ablations.

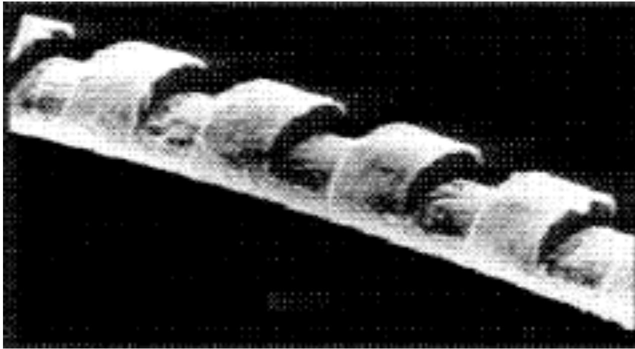

Figure 2. This well-known photograph shows notches etched in a human hair by an excimer laser. It demonstrates the potential precision of excimer laser ablations.

b. **Photocoagulation**. Tissue is heated 10-20 degrees C above normal. This coagulates blood and protein and stimulates a local inflammatory response. This results in scarring, adhesions and contraction of collagen. This reduces the oxygen requirement of the tissue. An example of this tissue effect is *pan-retinal photocoagulation (PRP) using the Argon (514-nm green) or **Krypton** (647-nm red) lasers, or **argon** laser trabeculoplasty (ALT)*. The amount of energy absorbed depends on the amount of pigment present, so pigmentation is an important consideration in photocoagulation.

c. **Photodisruption**. Very high energy instantaneoulsly heats tissues 15,000 degrees C, and this causes a microscopic explosion. An optometric clinical application is ***capsulotomy** using a **Nd:YAG laser** (1064-nm IR), which blasts a hole* in the opaque capsule behind an IOL. This process does not require pigment to transfer energy to the tissues.

Figure 3, (adapted from Carr LW, Talley DK. Laser-Tissue Interactions, in Optometry Clinics - Ophthalmic Lasers. Appleton & Lange, 1995) illustrates the three different kinds of effects on ophthalmic tissues.

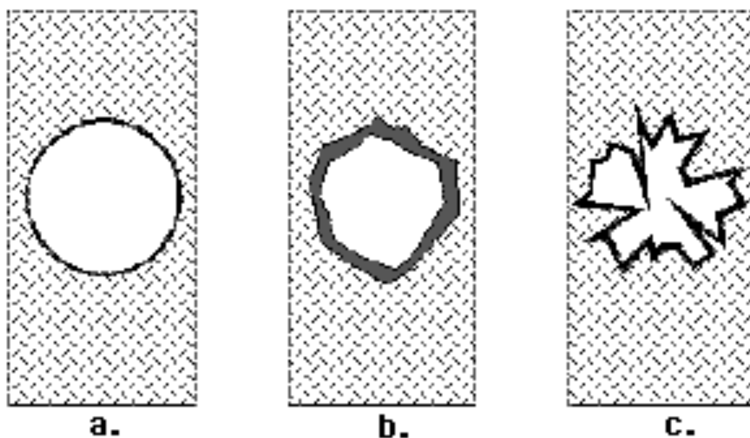

Figure 3 Examples of the three kinds of laser-tissue interactions: photoablation (a), photocoagulation (b) and photodisruption (c).

For the laser to have an effect on the tissue, the energy must be absorbed. Refer Table 1 and note where the different wavelengths are most strongly absorbed in the eye. This helps you to understand why, for example, an excimer laser (UV-C) is used to treat the cornea, a Nd:YAG (IR-A) is used to treat the capsule, and lasers in the visible spectrum are used to photocoagulate pigmented tissue in the retina and choroid. Laser-tissue interactions are summarized in Table 3.

In therapeutic applications, laser procedures are designed to produce controlled destruction of ocular tissues. You will study this in detail next summer in the laser technology course. In this course we will study how to protect the eye from unplanned or unwanted tissue damage caused by lasers.

Table 3. Laser applications in eye care.

Type	***photoablation***	***photocoagulation***	***photodisruption***
Description	vaporize	cook	explode
Example laser	excimer (193 nm)	argon (514 nm) krypton (647 nm)	Nd:YAG (1064 nm)
Clinical application	LASIK, PRK	ALT, PRP	capsulotomy

LASER PROTECTION

Lasers are in widespread use in medical facilities, industry, schools, in store checkout lines and in many homes (CD and DVD players). In all of these environments the laser is a potential ocular hazard. In an optometrist's office, for example, an assistant may be accidentally exposed if a laser beam reflects off an optical surface and enters his eyes. In a factory or research lab a person may accidentally look directly into a laser beam. Laser pointers are becoming increasingly popular even among children, and these may become a public health hazard. In response to this problem, some cities, such as Broken Arrow, Oklahoma, have made laws against flashing people with lasers. A few years ago there was a case of a man who was arrested and charged for flashing a commercial airliner with a laser.

A 1999 AOA Journal article by Yolton points out that laser pointers can indirectly be hazardous in another way. Laser gun sights (Fig. 3), like laser pointers, use a red diode lasers; they allow a shooter to accurately aim without bringing the gun to eye level. They are particularly well suited to dimly lit conditions when traditional sights are difficult to see. Quoting from Yolton (see references at the end),

> *For example, concern has arisen because small lasers can also be used as sighting devices for firearms. This has added considerably to the risk of laser-play, because it is difficult for a person—especially a police officer—to know whether the red spot projected on his or her body is from a pointer or a gun sight. It is probably only a matter of time before an officer "returns fire" toward a person aiming a laser pointer from a dark alley.*

Figure 3. One example of a laser gun sight.

During my research at Indiana University I built a Shack-Hartmann aberrometer, which shines a laser beam directly into the eye and measures the light reflected out. Before starting my experiments, I studied laser safety to ensure that I wouldn't blind my subjects, one of whom was my Ph.D. advisor! As Oklahoma optometrists, and NSU OCO graduates, people will assume that you are knowledgeable about lasers. You should be familiar with the principles of laser safety.

We will discuss the following principles of laser safety:

- Case example of a laser injury
- Laser classification
- Theoretical basis of exposure limits
- Computation of exposure limits
- References for laser safety information

CASE EXAMPLE OF A LASER INJURY - a laser accident victim's report of his experience (From Matthews L. *Laser and Eye Safety in the Laboratory*. IEEE Press, 1995.)

> *The necessity for safety precautions with high-power lasers was forcibly brought home to me last January when I was partially blinded by a reflection from a relatively weak neodymium:YAG laser beam. Retinal damage resulted from a 6 mJ, 10 ns pulse of invisible 1064 nm radiation. I was not wearing protective goggles at the time, although they were available in the laboratory. As any experienced laser researcher knows, goggles not only cause tunnel vision and become fogged, they become very uncomfortable after several hours in the laboratory.*
>
> *When the beam struck my eye I heard a distinct popping sound, caused by a laser-induced explosion at the back of my eyeball. My vision was obscured almost immediately by streams of blood floating in the vitreous humor, and by what appeared to be particulate matter suspended in the vitreous humor. It was like viewing the world through a round fishbowl full of glycerol into which a quart of blood and a handful of black pepper had been partially mixed. There was local pain within a few minutes of the accident, but it did not become excruciating. The most immediate response after such an accident is horror. As a Vietnam War veteran, I have seen several terrible scenes of human carnage, but none affected me more than viewing the world through my blood-filled eyeball. In the aftermath of the accident I went into shock, as is typical in personal injury accidents.*
>
> *As it turns out, my injury was severe but not nearly as bad as it might have been. I was not looking directly at the prism from which the beam had reflected, so the retinal damage is not in the fovea. The beam struck my retina between the fovea and the optic nerve, missing the optic nerve by about 3 mm. Had the focused beam struck the fovea, I would have sustained a blind spot in the center of my field of vision. Had it struck the optic nerve, I probably would have lost the sight of that eye.*
>
> *The beam did strike so close to the optic nerve, however, that it severed nerve fiber bundles radiating from the optic nerve. This has resulted in a crescent-shaped blind spot many times the size of the lesion. The effect of the large blind area is much like having a finger placed over one's field of vision. Also, I still have numerous floating objects in the field of view on my damaged eye, although the blood streamers have disappeared. These "floaters" are more a daily hindrance than the blind areas, because the brain tries to integrate out the blind area when the undamaged eye is open. There is also recurrent pain in the eye, especially when I have been reading too long or when I get tired.*
>
> *The moral of all this is to be careful and to wear protective goggles when using high-powered lasers. The temporary discomfort is far less than the permanent discomfort of eye damage.*

LASER CLASSIFICATION

The American National Standards Institute (ANSI) and the Bureau of Radiological Health (BRH) developed a system to categorize lasers according to their potential for retinal injury, with Class I being the safest and Class IV the most dangerous groups. The dividing line between the different classes was based on the ANSI exposure limits, which will be described later. Table 4 summarizes the classifications for visible wavelength lasers. The Shack-Hartmann sensor I built at Indiana University had a power output of 10 mW, which is a Class IIIb laser. This presents no retinal hazard for diffuse reflections, but in the case of direct viewing (my use), it had the potential to burn the retina faster than the blink reflex. Special safety precautions then, are required when using lasers at the Class III level or higher. Note that most laser pointers are Class III lasers. **Some people downplay the ocular hazard of common laser pointers, but you should keep in mind that, according ANSI, they are Class III devices and should be considered ocular hazards.**

Table 4. Laser classification

Class	*Description*	*Maximum power*	*Comment*
I	exempt	< 0.38 mW or enclosed	No ocular hazard
II	low power	< 1 mW	Safe within blink reflex time (0.25 sec)
IIIa	medium power	1- 5 mW	2 sec macular burn in monkeys (Lappin, 1970)
IIIb	medium power	5 - 500 mW	No skin burn for < 1 sec. No hazard for diffuse reflections.
IV	high power		Potential fire hazard

THEORETICAL BASIS OF EXPOSURE LIMITS

Prior to the first ANSI laser standards in 1973, different standards had been developed by the military, industry and others who use lasers. Now however, the booklet **ANSI Z136.1** (*The American National Standard for the Safe Use of Lasers),* has become the accepted laser safety standard in the United States and for the World Health Organization. These notes are based on the former ANSI Z136.1 version. The newest version became available from the Laser Institute of America on May 4, 2007, so I haven't seen it yet. The ANSI standard covers a wide range of laser safety topics, but for the purposes of determining safe exposure limits, the most important information is summarized in Table 5, below. *Note that these limits are expressed in terms of laser energy or power entering the eye, not energy or power at the retina.*

Visible light is highly absorbed by the retinal pigment epithelium and is transformed to heat, which dissipates into the surrounding tissues. The choroidal vasculature provides the main heat shunt, and thermal injuries occur when the temperature increase exceeds heat removal. The threshold for thermal injury thresholds is complex and depends on a many variables, such as wavelength, optical aberrations, exposure time, spot size, retinal location, pigment density, eye movements, and body temperature. Therefore, it is nearly impossible to determine the precise threshold for every person.

Table 5 is an excerpt from the ANSI laser safety standards. These standards were based on the best available experimental data, but in some cases the exposure limits had to be extrapolated or simplified. Most of the data came from experiments that titrated laser power and exposure times to determine thresholds for retinal damage that could be observed by ophthalmoscopy, but some also used histological studies or thresholds for visual loss. ANSI reviewed the available experimental data and established standards based on worst case-assumptions plus a reasonable safety margin. One of the important parameters included in the development of the standards shown in Table 5 is an *assumed pupil size of 7 mm*.

Table 5. ANSI Z-136.1 exposure limits for visible light.

Wavelength (nm)	*Exposure time (sec)*	*Maximum permissible exposure*
400 to 700	10^{-9} to 18 x 10^{-6}	0.5 x 10^{-3} mJ/cm^2
400 to 700	18 x 10^{-6} to 10	$1.8t^{3/4}$ mJ/cm^2
550 to 700	10 to 452	$1.8t^{3/4}$ mJ/cm^2
550 to 700	452 to 10^4	175.79 mJ/cm^2
400 to 700	10^4 to 3 x 10^4	17.58 x 10^{-3} mW/cm^2

CALCULATION OF SAFE EXPOSURE LIMITS

Table 5, taken from ANSI Z136.1, specifies the exposure limits for direct viewing of a laser and is the basis for most ocular laser safety calculations. Other tables are available that specify the exposure limits for diffuse reflections or for skin exposure.

To know whether a laser is safe or not, you must compare it's output power to the safe exposure limit. You should not expose the eye to any laser that exceed the safe limit. The problem is that the laser's strength is specified according to power output in milliwatts, but Table 5 lists safe exposure limits in terms of mJ/cm^2. You must go through several steps to determine the safe exposure limit based on the ANSI standard. I will illustrate the procedure with the computations I did for my research.

a. Energy flux. The first step is to compute the maximum permissible exposure (MPE) in terms of energy flux at the cornea. To compute this, you must know the *wavelength* of the laser and the *exposure time*. For a helium-neon laser with a wavelength of 633 nm and exposure time of 2.0 seconds, Table 5 shows that the MPE is equal to:

$$MPE = 1.8t^{3/4} \quad (mJ/cm^2)$$

Substitute time the value for time (t) in seconds into the formula. In this example t = 2.0 sec.

$$MPE = 1.8(2^{3/4}) = 3.027 \quad (mJ / cm^2)$$

b. Energy. *Energy flux* gives the safe exposure limit in terms of energy per square centimeter, as if the energy were evenly distributed across the incident beam. Assuming a 7-mm pupil, how much *energy* would enter the eye with this energy flux? For laser safety calculations, *a 7-mm, aberration-free pupil is assumed*, a worst-case assumption.

> Q. Why would exposure through a 7-mm, aberration-free pupil be more dangerous than exposure through a smaller pupil, or for a large pupil with aberrations?
>
> A. For smaller pupil sizes, diffraction cause the retinal focal spot to spread and energy will be less concentrated. For large pupils, aberrations also serve to blur the retinal spot, reducing the concentration of energy. Both of these reduce the potential for laser damage.

To determine the safe *energy* (not *energy flux*), the MPE must be multiplied by pupil area, which is 0.3848 cm^2, based on a pupil diameter of 0.7 cm. Note that, for the purposes of doing the calculation, pupil size was converted to centimeters. Thus, the 2-second energy exposure limit (E) is 1.165 mJ.

$$E = 3.027(0.3848) = 1.165 \quad (mJ)$$

c. Power. We really want to know the safe exposure limit at the cornea in terms of *power* rather than energy since *laser output is expressed in terms of power*, and this is what is actually measured by laser power meters. Power (P) is equal to energy (E) divided by exposure time (t) and the limit, computed below, is 0.5825 mW or about 0.6 mW.

$$P = E/t = 1.165/2.0 = 0.5825 \quad \text{(mW)}$$

When preparing to expose subjects to lasers, most scientists provide an additional margin of safety by reducing power below the ANSI limit. In my research, I decided not to expose subjects to more than one one-hundredth of the ANSI limit. For a 2-second continuous exposure to the helium-neon laser, my power limit was therefore 0.006 mW or 6μW. This may seem like a very small amount of power, but subjectively, this was very bright! (I myself on the Shack-Hartmann device before I measured subjects.)

DETERMINING IF THE LASER IS SAFE OR NOT

Having computed the safety limit in terms of power at the eye, I then had to see if my laser was within that safety limit. The power output of a laser is printed on the laser, and is on the spec sheet. In addition, I used a laser power meter to measure the actual power of the laser. In my case, the laboratory laser had a power output of 10 mW. For comparison, most laser pointers produce about 5 mW of power, which is 833 times stronger than my self-imposed limit of 6 μW. My laser was 1667 times too strong (computation below)! Since my laser was much too powerful to let someone stare at for 2 seconds, I had to reduce its power. I did this by placing neutral density filters in front of the laser until the power had been attenuated to an acceptable level. The next section explains how to compute the appropriate ND filter to accomplish this.

NEUTRAL DENSITY FILTER COMPUTATION

The appropriate neutral density should first be estimated as follows:

First determine how much the laser exceeds the safety limit, by dividing the laser power by the safety limit. This is the required attenuation factor. Neutral density filters are labeled in log units, so we must compute the log of this attenuation factor. If, for example, the power of the laser is 10 mW, and we want to reduce power to .006 mW, the power must be attenuated by the ratio,

$$10/.006 = 1{,}667.$$

$$\log(1{,}667) = 3.22$$

Therefore a 3.3 ND filter should attenuate the laser energy (and power) to a safe level.

People working in a laboratory with a 10 mW laser must wear special **laser safety glasses** that

- have at least this optical density (3.3 ND), and
- **protect for the wavelength of the laser** (in this case 633 nm).

Laser safety glasses must be designed for the specific wavelength the person may be exposed to. For use around a helium-neon laser (red), the lenses are blue, since they absorb long wavelengths but pass short wavelengths. Since they pass short wavelengths the person is able to see what he is doing in the laboratory.

Note that a 3.3 ND filter is VERY dark. Its transmittance is just 0.06%. It is clear that normal sunglasses, which typically transmit 15-40% of the incident light, cannot provide adequate laser eye protection in this example.

In summary, determine the laser hazard using the following steps.

- Know the laser wavelength and expected exposure time
- Find the formula in ANSI Z136.1 Table 5 for that *wavelength* and *time*.
- Enter time into the equation and compute the exposure limit in mW using the steps described above. This gives the exposure power limit for direct viewing. You may want to add an additional safety factor.
- Compare this to the actual laser power. **You should measure the laser power, rather than trust the power label.** If the laser output power is larger than this safety limit, you must attenuate the power. You can reduce laser power using neutral density filters or provide the patient with appropriate laser safety glasses.

REFERENCES

Two important laser safety publications may be obtained from the Laser Institute of America. Their web address is: http://laserinstitute.org/

ANSI Z136.1 - 2007 *Safe Use of Lasers* (New edition released March 15, 2007)
ANSI Z136.3 - 2005 *Safe Use of Lasers in Health Care Facilities*

The best comprehensive reference on laser safety, which is also very well written is:
Sliney D, Wolbarsht W. *Safety with Lasers and Other Optical Sources.* Plenum Press, New York, 1981.

Other references:
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