Non-Therapeutic Laser Retinal Injury

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ABSTRACT

BACKGROUND: As lasers have become an increasingly important component of commercial, industrial, military, and medical applications, reported incidents of non-therapeutic laser eye injuries have increased. The retina is particularly vulnerable due to the focusing power and optical transparency of the eye. Continued innovations in laser technology will likely mean that lasers will play an increasingly important and ubiquitous role throughout the world. Critical evaluation should thus be paid to ensure that non-therapeutic injuries are minimized, recognized, and treated appropriately.

METHODS: A comprehensive literature review on the PubMed database was conducted to present case reports and case series representative of the variety of laser eye injuries in different injury circumstances, tissue types, and biological damage mechanisms.

RESULTS: A general summary of non-therapeutic laser retina injuries is presented, including information about growth of the industry, increasingly accessible online markets, inconsistent international regulation, laser classifications, laser wavelengths, and laser power, mechanisms of tissue injury, and a demonstration of the variety of settings in which injury may occur. Finally, 68 cases found in the literature are summarized to illustrate the presentations and outcomes of these patients.

CONCLUSIONS: As non-therapeutic laser eye injuries increase in frequency, there is a greater need for public health, policy, diagnosis, and treatment of these types of injuries.

Key words: Laser; Injury; Retina; Photocoagulation

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INTRODUCTION

Lasers are increasingly used for medical, industrial, commercial, military, research, and entertainment purposes, spurred by rapid technological development, decreasing size, and decreasing costs. The continued proliferation of laser use and their relative ease of unregulated purchase have resulted in concern over the consequences of unintended or malicious laser eye injuries. As they have increased in popularity, so have the incidents of accidental laser use injuries. Figure 1 demonstrates a handheld laser pointer that is commercially available online.

In 1997, the United States Food and Drug Administration (FDA) warned that lasers could be “more damaging than staring directly into the sun,” and imposed regulations on laser sales. That same year, the British government banned Class III lasers due to retinal damage from direct exposure. In 1998, the World Health Organization (WHO) warned of handheld laser pointers that are “too powerful for general use” that pose “an unacceptable risk in the hands of
The growing use of lasers and increasing cases of non-therapeutic laser injury underscores the importance of understanding the scope and types of non-therapeutic laser eye injuries. This review will evaluate the means and mechanisms of injury in terms of the wavelengths at risk, current policies governing laser regulations, laser principles and specific tissue injuries, imaging modalities for identifying real from imagined laser eye injuries, and cases and types of injuries reported in the literature.

RISK WAVELENGTHS

Wavelengths between 400 nm and 760 nm are recognized as visible light, whereas wavelengths outside of this range also reach the retina. The eye is designed to focus light on the retina, primarily by the tear film, cornea, and lens. The cornea only transmits photons greater than 295 nm. The lens absorbs almost all wavelengths near 400 nm, including some blue and ultraviolet (UV) light. The lens with age absorbs more UV-A. There are lens filters that block 99% of the UV spectrum from reaching retina[19]. The retina itself has evolved to capture photons efficiently and initiate visual transduction. Overall, the focusing power and anatomical function of the eye means that retinal tissue is particularly susceptible to laser-induced injury[20].

Typically, handheld laser pointer energy is insufficient to cause injury at the ocular surface. However, greater than 100-fold amplification of irradiance by the ocular media and focusing power of the eye make the retina particularly susceptible to laser eye injury. Anterior segment injuries from handheld lasers are rare, while blink response (average aversion time 0.25 seconds), pupillary constriction and aversion to laser light brightness are usually protective. With greater than 5 mW lasers, the power may be too great for our natural defenses, resulting in severe, permanent damage with vision loss. Minor foveal injury and macular sparing are good prognostic signs for visual recovery[21].

LASER AND REGULATION

Laser stands for Light Amplification by Stimulated Emission of Radiation. It was first developed in 1960[22]. Lasers are monochromatic, coherent, and non-divergent[23]. A laser is composed of three basic elements: an active medium, a resonant cavity, and an excitation or pumping mechanism. Specific laser properties depend on the stimulated element, molecule, or compound (Figure 2).

Examples of commonly used lasers in ophthalmology include:
1. Visible spectrum (400-700 nm): Argon (blue-green and green), Krypton (yellow and red), tunable dye, helium-neon, frequency-doubled Nd:YAG; (2) Infrared: Nd:YAG and carbon dioxide (CO2); (3) Ultraviolet (UV): Excimer.

The American National Standards Institute (ANSI)[24] establishes maximum permissible laser radiation exposure an unprotected person may receive without biological consequence as measured by tissue samples and imaging[25,26,27,28,29,30]. They classify lasers by output.

Class I (< 0.4 mW) are used in optical instruments for intrabeam viewing. They do not cause damage even with long-duration retinal exposure.

Class II (< 1 mW) and Class IIIA (1-5 mW) cause retinal damage if viewed greater than 10 s at close range. These lasers rely on our natural aversion to bright lights, which is impaired for instance by altered mentation, malice, or curiosity. Class IIIf was initially thought to be innocuous unless viewed greater than 10s, but some studies in to-be-enucleated eyes have demonstrated histopathologic changes[31].

Class IIIB and IIIR (5-500 mW) are hazardous and prohibited in
Figure 2 Representation of a variety of handheld, commercial, and medical laser wavelengths. Paulausky, C. Laser Safety: The Eyes Have It! Occupational Health & Safety. August 2, 2014. https://ohsonline.com/Articles/2014/08/01/Laser-Safety_0.aspx.

many countries but are readily available online\(^{32}\).

Class IV (greater than 500 mW) have military applications and can produce extensive ocular damage.

United States laser sales are regulated by the Food and Drug Administration Code of Federal Regulations, which requires compliance for Class I, II, IIA and IIB devices. Many countries and international Internet sales are unregulated or unenforced\(^{33}\). For instance, a quick Internet search yields a 6 W laser available for purchase that exceeds the ANSI safety limits by greater than 20,000 times and requires only 10 milliseconds to cause damage, far faster than the blink reflex. In Europe, EN 60825/207/208 provides regulation for safe laser use and necessary protective equipment by limiting exposure respect to energy per unit of beam area with no allowance for diffuse viewing conditions. The American standard, ANSI, which has been adopted by many Asian countries, specifies protective eyewear requirements in terms of optical density (OD) and allows for a nominal hazard zone to be determined by a laser safety officer outside of which diffuse viewing eyewear is allowed. Whereas optical density requirements allow for a diffuse viewing condition, a code that regulates permissible energy density will more specifically protect against direct beam exposures and protects against diffuse exposure that rises above threshold energy limits.

The United Nations 1980 Convention on Certain Conventional Weapons (CCW) Protocol IV, “Protocol on Blinding Laser Weapons,” came into force on October 13, 1995, and is the first international agreement regulating the use of lasers as weapons during combat\(^{161}\). It specifically prohibits the use of blinding laser weapons in warfare that are designed to cause permanent blindness and requires precaution to prevent blindness when non-combat laser systems are employed in combat. The agreement was the first time since the banning of explosive bullets in 1868 that the international community as pre-emptively banned a destructive technology from warfare prior to its widespread implementation on the battlefield\(^{162}\). Prior to the ban, however, laser weapons had already been developed that specifically target the eye. For instance, the U.S. developed a shoulder-mounted laser rifle with a beam diameter of 1 m and blinding range of 1 km. China had a similar, tripod-based weapon with a purported blinding range of 2 km to 3 km and the capability to sustain two simultaneous wavelengths at 15 mW for 5 minutes\(^{159}\). As of January 28, 2018, 108 nations have agreed to the treaty\(^{160}\).

The U.N. agreement does not limit blinding as an incidental effect of non-intentionally blinding laser systems. The ban also does not remove potentially blinding equipment such as range finders and target illuminators from combat, despite their potential for use as intentionally blinding weapons. This issue was well-framed by British ophthalmologist John Marshall in BMJ in 1997, noting that a wide variety of not-specifically-weapon lasers were still being used as weapons on the battlefield\(^{161}\). Incidental injuries have also been a problem unaddressed by the agreement, as blinding lasers are still used for a variety of battlefield purposes that include range-finding, target designation, antisensors, and antimaterial systems designed to disable equipment but could be used on humans as well, in violation of the UN agreement\(^{164-168}\). Currently, there are also laser systems developed for the battlefield that intend to create a temporary glare effect in enemy soldiers, and it is likely that these anti-personnel weapons will continue to be developed\(^{169}\).

**LASER-TISSUE INTERACTIONS**

As light energy reaches the retina, its deposition, penetration and/or absorption depends on wavelength, duration of exposure, and composition of retinal tissues. When energy deposition is too low or dispersion is too high, oxidative photochemical damage occurs via absorption of photons. If deposition is greater than thermal dispersion, and resulting tissue temperature increase is greater or equal to 10°C, photothermal damage occurs. Nonlinear damage can
occur via sheer stress and cavitation if energy deposition is faster than tissue relaxation. Ultra-short high energy lasers can create very precise locally extreme heat to 10,000°C, causing photodisruptive damage[34]. Tissue response to absorbed energy can include photocoagulative, photothermal, and photodynamic injury[35]. Injury types are dependent upon power density, total exposure duration, and wavelength of irradiating energy, which are affected by wavelength-dependent properties of the anterior segment and vitreous[36].

Laser light localized to the retina is the most important determining factor for injury. Retinal injury from lasers range from subclinical to full-thickness macular holes with impaired choroidal perfusion[37]. Visual loss is greater at the fovea; peripheral injury is less symptomatic. Risk factors that increase injury include large pupil size due to increased transmission, and increased retinal and choroidal pigmentation due to the broad absorption spectrum of photon energy by melanin in the retinal pigment epithelium (RPE)[38].

Injury may occur at different retinal layers based upon duration, wavelength, and power of laser. For instance, green light undergoes less angular spreading than red light, making it more harmful. Green laser light (532 nm) may be additionally harmful due to its wavelength near the peak-sensitivity of dark-adapted eyes[39]. Utilizing blue light for macular photocoagulation can result in damage to the inner neurosensory retina.

Tissue composition is also important in determining absorbance and resultant injury within specific layers of the retina[40]. (Figure 3) Xanthophyll pigment is concentrated in the macula and has susceptibility to blue light damage due to its peak absorbance. Xanthophyll is abundant in the retinal nerve fiber layer (RNFL), inner plexiform layer (IPL), and outer plexiform layer (OPL), leaving these tissues and the inner retina particularly susceptible[41]. Hemoglobin absorbs mostly blue, green and yellow wavelengths. Melanin absorbs broadly across the visual spectrum. Laser-induced injury pathology has been studied on eyes scheduled for enucleation[42,43], and with animal models[44,45,46]. Advanced imaging technology now allows for recognition and study of previously-undetectable light-induced retinal injury and their relationship to wavelength, power, and duration[47]. Morgan et al. in 2008 demonstrated via adaptive optics scanning laser ophthalmoscope (AOSLO) retinal pigment epithelium (RPE) autofluorescence changes induced by 568-nm light exposure at a power level at or near current laser safety standards[48]. Since then, optical coherence tomography (OCT), fluorescein angiography (FA), adaptive optics (AO), and other technologies have emerged that are detecting previously-underappreciated or undetected damage[49,50]. This includes sub-RPE choriocapillaris damage[51] in subtle[52], early[53], and chronic solar retinopathy[54,55,56,57]. A 2014 paper from Pocock et al. in the Journal of Ophthalmology evaluated in vivo imaging of photothermal, photochemical, and photomechanical retinal laser injury in cynomolgus monkeys. They identified unique characteristics for each type of tissue injury, and noted that high resolution images are better at detecting laser eye lesions[58].

Photocoagulation

Argon and krypton wavelengths are primarily absorbed by hemoglobin and melanin, which then increase in temperature resulting in protein denaturation and tissue breakdown. Therapeutic applications of photocoagulative tissue injury include treatment of proliferative diabetic retinopathy, retinal vein occlusion, retinal capillary hemangioma, and choroidal tumors[59].

Photocoagulative therapy is typically performed with continuous 514-532 nm green, 577 nm yellow, or 647 nm red laser with 100-

Figure 3 Absorption spectrum of several important ocular pigments. Lock JH-J, Fong KCS. An update on retinal laser therapy. Clinical and Experimental Optometry. 2010;94(1):43-51.
200 millisecond (ms) pulses, 100-500 micrometer spot size, and 100-750 milliwatt (mW) power. Panretinal photocoagulation has been proven to be effective at halting angiogenesis, but it can cause scarring and decreased peripheral, color, and night vision. Focal and grid laser photocoagulation are effective for treatment of macular edema, but can cause scotoma and scarring. Damage surrounding the treatment area can adversely affect patients. Complications include retinal atrophy, thinning, scotomas, post-laser lesion enlargement, choroidal neovascularization, subretinal fibrosis, and visual field loss[60]. Attempts to limit side-effects include adjusting pulse duration, spacing, intensity, and axial localization[61,62].

Modulating wavelength may also minimize certain side-effects. For example, yellow (577 nm) laser for photocoagulation may reduce the risk of Bruch’s membrane rupture as compared to 532 nm green laser[63].

There is a growing research basis for understanding retinal tissue recovery following certain patterns of laser injury. Following inner-retinal-neuron-sparing selective laser photocoagulation, rabbit retinal neurons exhibit plasticity by changing connectivity to restore anatomy and function[64]. The continuity of the photoreceptor layer can also be restored in rabbit and rodent models following selective photocoagulation. RPE coverage restoration takes places within days, followed by the photoreceptor layer weeks to months later[65,66]. Photoreceptors filling a lesion likely migrate from adjacent healthy areas[67,68]. c-Met facilitates RPE migratory response in response to laser-induced retinal injury[69]. (Figures 4 and 5) demonstrate histologic characteristics of semi-automated pattern scanning retinal photocoagulation and Nd:YAG photocoagulation respectively.
Photothermal
Photothermal damage occurs by transfer of photon energy from light to retinal molecules, provided that the difference between the molecule’s energy states is equal to that of the photon. Photothermal damage tends to occur at longer (red-shifted) wavelengths and shorter pulses, and tends to be irreversible when ambient temperature of the retina increases by 10°C. Cells may undergo apoptosis with varying degrees of necrosis up to 68°C, and immediate cell death above 72°C[56]. Photothermal absorption occurs especially within melanin (RPE melanosomes and choroid melanocytes), xanthophyll (Müller cells and neurosensory retina), and hemoglobin (retinal and choroidal blood vessels)[57]. Photothermal tissue injury is utilized therapeutically in transpupillary thermotherapy (TTT) procedures, which were introduced in 1995[58]. TTT has been applied for treatment of choroidal tumors[59], retinoblastoma, choroidal neovascularization[60], and age-related macular degeneration[61].

Photochemical
Photochemical injury is independent of the energy transfer required for photothermal and photococagulation. It occurs by generating free radicals from light incident on retinal tissue. It predominates at long exposures of short wavelength (i.e. blue light over time)[62]. Energy requirements for photochemical damage have also been described on a continuum with requirements for photothermal damage[63].

Photochemical injury occurs primarily in the outer layers of the central retina principally by short-wavelength exposures. It is by this mechanism that solar retinitis, iatrogenic ophthalmic instrument injury, and blue light-induced age-related macular degeneration (ARMD) are likely to occur. Cell death is via apoptosis. Injury by photochemical injury is classified as follows. Class I damage is via rhodopsin action spectrum mediated by visual pigments with primary lesions in photoreceptors. Action spectrum is heightened with higher frequency, which explains why blue lights are particularly harmful. Class II damage occurs at the RPE[64]. Blue and UV light are more onerous at lower powers because their short wavelength induces greater action spectrum within photoreceptors[65]. Michael and Wegener estimated safe exposure times to avoid photochemical injury for different light sources based on American Conference for Governmental and Industrial Hygienists data on the Zeiss operation microscope OPMI VISU 200[66].

In an Agouti rat model, blue light (405nm, 3.2mW/cm²) damage applied over 2 hours resulted in photoreceptor apoptotic death, and cellular damage in the outer retina[67]. In an early study, low power blue light (441 nm) sustained for 16.7 minutes resulted in nonthermal, photochemical damage to RPE with histological response and hypopigmentation after 48 hours[68]. RPE expresses L-type calcium channel α1D subunit, vascular endothelial growth factor (VEGF) and basic fibroblast growth factor (bFGF) in response to blue light in vitro[69].

Photococagulation
Photococagulation is the basis for photothermal injury. This can be achieved by a variety of laser sources and is now used in minimally invasive surgery i.e. Nd:YAG laser[70]. Near-infrared 1030-1064 nm femtosecond lasers that utilize photodisruptive tissue injury are used therapeutically in femtosecond-assisted cataract surgery to add precision and reproducibility. Energy transmitted to the retina and choroid may damage these tissues due to wavelength-absorbing melanosomes in the RPE and pigmented choroid that can cause damage via microbubble formation, shockwave damage, and cumulative thermal damage[71].

Distinguishing True from False Cases of Laser Eye Injury
Interestingly, complaints of accidental laser eye injuries are for more numerous than confirmed instances of retinal injury, with less severe cases more being difficult to diagnose. Symptoms of laser-induced ocular injury include decreased visual acuity, scotoma, photophobia, metamorphopsia, and chromatopsia. Chronic ocular, facial, and head pain are not attributed to laser pointer injury. Redness and irritation are similarly non-attributable. Signs include linear streaking and hypofluorescence on FA, and visible lesion on dilated fundus examination. AOSLO, fluorescein angiography (FA), fundus autofluorescence (FAF), OCT, and infrared (IR) have also been used to characterize lesions[72]. Mainster et al. present a 5-case series along with series of 6 questions to aid in evaluating real or imagined laser eye injury. The following question and case series can be used to aid in evaluation[73].

1. Are there ocular abnormalities that could have been caused by a known laser-tissue interaction at the time of the reported incident?
2. If so, have those abnormalities been documented by a reliable technique, such as fundus photography, fluorescein angiography, or optical coherence tomography?
3. If so, do findings from ophthalmoscopic and retinal imaging evolve after the incident in a manner consistent with a laser injury?
4. If so, and substantial visual or somatic complaints are present, is there any scientific evidence that the objective ocular findings could cause the reported subjective complaints?
5. If so, and substantial visual complaints are present, is the location of Amsler grid or visual field defects stable and consistent with the location of the retinal abnormalities supposedly responsible for causing them?
6. If the laser source involved in the alleged injury is available or known, is it capable of producing the observed clinical findings under the reported exposure conditions?

Mainster’s example cases:
The article goes through several sample cases of applying the above 6 criteria to an evaluation of alleged laser eye injury.

Case A. 11-year-old girl >10 seconds staring at red laser pointer resulting in painless scotoma. Central foveal pigment mottling and faint hyperfluorescence on evaluation 3 weeks later. Vision returned to 20/25. Yes, likely due to laser injury.

Case B. Middle-age woman momentarily exposed to ordinary laser pointer. 4 years later developed headaches, photophobia, and pains. No pathology on FA or slit lamp other than dry eye. 20/20 OU. Not likely due to laser injury.

Case C. Young male soldier accidentally exposed to q-switched 1064 nm range finder laser pulses resulting in painless decrease in vision. At 24 hours: vitreous hemorrhage overlying 2 foveal retinal holes. At 5 days: “3 prominent chorioretinal lesions with surrounding hyperfluorescence.” Visual acuity at 18 months: 20/400. Not due to...
A comprehensive literature review was performed on PubMed using a variety of search terms related to laser eye injuries, handheld lasers, laser retinopathy, and laser pointer damage. What follows is a sample of cases reports found in the literature that illustrate the variety of presentations and contexts for injury.

### Military

Military and industrial lasers injure an estimated 15 people annually. A 2003 case review series published on military laser retinal injuries included 10 cases from 1984-2000, mostly by 1064 nm q-switched Nd:YAG range finding lasers. No corneal or anterior chamber injuries were reported. No individuals were wearing eye protection. Two received medical discharges as the result of their injuries. Authors suggest that unintentional injuries may be reduced by improving operator safety training and compliance, as well as improving equipment safety design features.

Accidental exposure to a hand-held Nd:YAG range finder laser in 2004 resulted in a full thickness foveal hole in a 20-year-old man.

### Industrial Cases

Industrial lasers injure an estimated 10 people annually. A 2003 case review series published in occupational safety and health literature included 9 cases from 1984-2000, mostly by 532 nm Q-switched Nd:YAG range finding lasers. No corneal or anterior chamber injuries were reported. Half of individuals were wearing eye protection. Two received medical discharges as the result of their injuries. Authors suggest that accidental injuries may be reduced by improving equipment safety design features.

### Table 1: Summary of Laser-Induced Retina Injury Case Reports Involving Military Exposures

| Military Cases | Age | Type of Laser | Interval from injury to presentation | Presenting BCVA | Interval from injury to follow-up | Final BCVA | Fundus Findings                  |
|----------------|-----|---------------|------------------------------------|----------------|---------------------------------|------------|----------------------------------|
| Harris (2003)  | 21  | 1064nm Q-switched Nd:YAG | Immediate                          | 20/400         | 12 months                       | 20/40      | Vitreous hemorrhage and three focal lesions |
|               |     | 632nm pulse-repetition Nd:YAG pumped dye laser | Immediate                          | 20/300         | 6 months                        | 20/20      | Macular hemorrhage                |
|               | 19  | AN/GVSS laser rangefinder, Q-switched ND:YAG | 1 day                              | 20/200         | 18 months                       | Count fingers | Subretinal hemorrhage within center of macular involving fovea, vitreous overlying hemorrhage appeared to be detached |
| Allen (2004)   | 21  | Nd:YAG range finder device | 24 hours                          | 20/25 OU       | 4 years                         | 20/200 OD | Bilateral macular holes and vitreous hemorrhages |
| Shenoy (2015)  | 27  | Blue-green unlabelled laser pointer | 1 day                              | 1/60           | 1 month                         | 1/60       | Vitreous hemorrhage                |
|               |     | Blue-green unlabelled laser pointer | 1 week                            | 1/60           | Lost to follow-up               | No visible lesion | Premacular subhyaloid hemorrhage |
| Noble (2015)   | 13  | Green laser pointer | 20/30                             | 20/30          | 2 months                        | 20/30      | No visible lesion                  |

### Table 2: Summary of Laser-Induced Retina Injury Case Reports Involving Industrial Exposures

| Industrial Cases | Age | Type of Laser | Interval from injury to presentation | Presenting BCVA | Interval from injury to follow-up | Final BCVA | Fundus Findings                  |
|------------------|-----|---------------|------------------------------------|----------------|---------------------------------|------------|----------------------------------|
| Zwick (1998)     | 21  | 1064nm Nd:YAG laser | 3 hours                           | 20/50          | 55 days                         | 20/20      | Small macular hemorrhages OU      |
| Newman (2000)    | 24  | 808nm Titanium:sapphire laser | 2 days                           | 20/200         | 139 days                        | 20/15      | Small vitreous hemorrhage, retinal injury on fovea |
| Sakaguchi (2000) | 24  | 1064nm Nd:YAG laser | 3 days                            | 20/100         | 1 month                         | 20/100     | Full-thickness macular hole       |
| Roider (1999)    | 25  | 1064nm Nd:YAG AVIMON Limited LD 900 Range Finder | 2 hours                           | 20/100         | 4 months                        | 20/130     | Large, prominent hemorrhage       |
| Kitaguchi (2009) | 24  | 4000nm Titanium:sapphire laser | 1 day                            | 20/25          | 1 month                         | 20/20      | Normal                           |
| Sun (2006)       | 22  | Pulsed Green Laser Light Beam | 5 days                            | 0.08 OD        | 12 months                       | 0.01       | Small grayish-yellow lesion with exudation at foveal area |
| Fujinami (2010)  | 11  | Green laser pointer | 8-9 years                         | 1              | 11-12 years                     | 1          | Yellow exudate-like lesion or fibrous tissue surrounded by subretinal hemorrhage |
| Milani (2011)    | 25  | 1064nm Nd:YAG laser | NA                               | 20/60          | 6 months                        | 20/20 OU   | Extended lesion involving foveal area with a deep, central hemorrhage |
Table 3 Summary of laser-induced retina injury case reports involving commercially-available devices.

| Commercial Cases | Age   | Type of Laser | Interval from injury to presentation | Presenting BCVA | Interval from injury to follow-up | Final BCVA | Fundus Findings |
|------------------|-------|---------------|--------------------------------------|-----------------|----------------------------------|------------|-----------------|
| Wyrsh (2010)     | 15    | Green laser pointer | 2 weeks                | 20/50 OD, Count fingers at 3ft OS | 4 months | 20/32 OD, 20/25 OS | Several tiny round scars in RPE of fovea OD, dense subretinal hemorrhage in macula OS |
| Ziahosseini (2010) | Teenager | Green diode laser pointer | NA | 6/12 OU | 2 months | 6/6 OU | Bilateral foveal granularity |
| Xu (2016)        | 12    | Green laser pointer | Shortly after injury | 20/20 OD, 20/30 OS | 7 months | 20/20 OD, 20/30 OS | Pigment clumping with focal RPE atrophy OU |
|                  | 9     | Green laser pointer | 4 days                  | 20/50 | 1 month | 20/30 | Macular pigment changes |
|                  | 16    | Green laser pointer | Immediate              | 20/30 OU | 2 weeks | 20/40 OU | Macular choroidal scars and focal RPE atrophy |
|                  | 12    | Red laser pointer  | Immediate              | 20/70 | 12 months | 20/20 | RPE atrophy and a choroidal neovascular membrane with subretinal hemorrhage |
| Hanson (2016)    | 11    | Class III green laser pointer | 9 months | 6/20 OD, 6/10 OS | 34 months | 6/15 OD, 6/7.5 OS | Hyper- and hypopigmented scars at foveas OU |
| Thanos (2015)    | 44    | Red laser pointer  | 6 months               | 6/6 | 19 months | 6/6 | Barely visible RPE disturbances within the temporal macula |
| Raof (2015)      | 9     | Hand-held laser device | 24 hours               | 6/15 | 19 months | 6/9 OU | Bilateral yellow macular lesions |
|                  | 11    | Laser device could not be obtained | NA | 6/7.5 OU | 12 months | 6/9 OU | Bilateral yellow macular lesions |
|                  | 8     | Hand-held laser device | Several months' | 6/12 | 12 months | 6/7.5 | Right foveal RPE changes consistent with laser burns |
| Lim (2014)       | 13    | Green diode laser   | 4 weeks                | 20/100 | 12 months | 20/60 | Hypopigmented area of RPE centrally, without subretinal hemorrhage |
| Lee (2014)       | 10    | Class III green laser pointer | 4 days | 20/30 | 18 months | 20/20 | Flat, deep diagonal foveal lesion comprised of central pigment clumping surrounded by hypopigmentation and window defect in areas of pigment loss |
|                  | 9     | Red laser pointer   | 4 days                  | Counting fingers at 3ft OU | 12 months | 20/100 OD, 20/70 OS | Bilateral, flat yellow foveal lesions with linear extension and RPE disruption radiating from fovea |
|                  | 6     | Class III green laser pointer | Several weeks | Counting fingers | 11 months | 20/100 | Flat, yellow foveal lesion with radiating streaks of RPE disruption |
| Alsulaiman (2014)| 17    | Blue laser beam     | 1 week                  | 20/40 | 2 months | 20/20 | Unremarkable except yellowish-orange discoloration at left fovea representing defect in outer retinal layers |
|                  | 30    | Blue laser beam     | 2 months               | 20/70 | 3 months | 20/30 | Full-thickness macular hole |
|                  | 11    | Blue laser beam     | 1 week                  | 20/300 | 11 weeks | 20/160 | Full-thickness macular hole |
|                  | 15    | Blue laser beam     | 2 days                  | 20/400 | 3 weeks | 20/50 | Full-thickness macular hole |
|                  | 18    | Blue laser beam     | 2 months               | 20/200 | 3 months | 20/40 | Full-thickness macular hole |
|                  | 15    | Blue laser beam     | 5 days                  | 20/300 | 12 weeks | 20/20 | Foveal sub-ILM hemorrhage |
|                  | 22    | Blue laser beam     | 3 days                  | 4/200 | 6 weeks | 20/40 | Subhyaloid hemorrhage |
|                  | 11    | Blue laser beam     | 5 days                  | 4/200 | 5 months | 20/25 | Subhyaloid hemorrhage |
|                  | 18    | Blue laser beam     | 2 hours                 | 4/200 | 4 weeks | 20/25 | Subhyaloid hemorrhage |
|                  | 20    | Blue laser beam     | 6 days                  | 20/100 | 4 weeks | 20/40 | Sub-ILM hemorrhage |
|                  | 17    | Blue laser beam     | 4 hours                 | 5/200 | 6 weeks | 20/15 | Subhyaloid hemorrhage |
|                  | 17    | Blue laser beam     | 1 day                   | 3/200 | 2 months | 20/50 | Subhyaloid hemorrhage |
|                  | 18    | Blue laser beam     | 2 months               | 20/200 | 5 months | 20/70 | ERM with SRF |
|                  | 16    | Blue laser beam     | 4 days                  | 20/70 | 2 months | 20/20 | Schisis-like cavity with SRF |
| Author            | Year | Laser Type                  | Duration 1 | Vision 1 | Duration 2 | Vision 2 | Findings                                                                 |
|-------------------|------|-----------------------------|------------|----------|------------|----------|--------------------------------------------------------------------------|
| Abdelkader (2016)| 20   | Class IVb blue handheld laser | 2 days     | 20/400   | 6 months   | 20/200   | Massive macular edema with a small dot hemorrhage below fovea            |
| Ueda (2011)       | 12   | Class IIIB green laser pointer | 1 day      | 24/20 OD, 24/20 OS | 6 months | 24/20 OD, 24/20 OS | Hypopigmented spot in fovea                                             |
| Turaka (2012)     | 13   | Class IIIA green laser pointer | 1 day      | 20/100   | 20/60      |          | Grey lesion in fovea                                                     |
| Lally (2014)      | 9    | Red laser pointer           | 4 days     | Counting fingers OU | 6 months | 20/200 OU               | Yellow-green foveal lesion with asymmetric radial spokes OU           |
| Bhavsar (2015)    | 18   | Red, Green, and Purple laser pointers | 3 weeks    | 20/25 OD, 20/40 OS | 8 weeks | 20/160 OD, 20/100 OS | Bilateral perifoveal RPE changes                                       |
|                   | 11   | Green laser pointer         | 1 day      | Hand motion | 1 month | Counting fingers at 5 feet | Deep, yellow foveal lesion and prominent gray-white linear streaks at level of outer retina in superior macula |
|                   | 14   | Unknown laser               | 5 weeks    | 20/50 OD, 20/70 OS | 9 weeks | 20/20 OD, 20/30 OS | Perifoveal RPE changes OD>OS                                             |
| Sayman (2016)     | 29   | Laser light at a wedding    | 3 days     | 3/10     | 1 year     | 10/10    | Foveal hemorrhage                                                       |
|                   | 9    | Laser at a hotel            | 15 days    | Counting fingers | 6 months | 9/10     | Foveal hemorrhage                                                       |
|                   | 24   | Laser light at an entertainment venue | 1 week     | 1/10     | 6 months   | 3/10     | Subretinal foveal hemorrhage                                             |
| Qi (2017)         | 26   | Nd:YAG laser                | 5 days     | 2/20     | 10 months  | 3/20     | Full-thickness Macular Hole                                             |
|                   | 21   | Nd:YAG laser                | Few hours  | 2/20     | 38 months  | 20/20    | Full-thickness Macular Hole                                             |
|                   | 27   | Nd:YAG laser                | 2 months   | 6/20     | 9 months   | 10/20    | Full-thickness Macular Hole                                             |
|                   | 38   | Nd:YAG laser                | 2 months   | 4/20     | 5 months   | 14/20    | Full-thickness Macular Hole                                             |
|                   | 35   | Nd:YAG laser                | 3-4 months | 6/20     | 45 months  | 20/20    | Full-thickness Macular Hole                                             |
|                   | 20   | N/A                         | 1 month    | Counting fingers | 7 months | Counting fingers | Full-thickness Macular Hole                                             |
|                   | 10   | Green handheld laser        | 1 month    | 1/20     | 28 months  | 16/20    | Full-thickness Macular Hole                                             |
|                   | 13   | Blue handheld laser         | 1 month    | 6/20     | 21 months  | 20/20    | Full-thickness Macular Hole                                             |
|                   | 14   | Green handheld laser        | 10 days    | 4/20     | 22 months  | 16/20    | Full-thickness Macular Hole                                             |
|                   | 32   | Blue handheld laser         | 2 days     | 6/20     | 13 months  | 20/20    | Full-thickness Macular Hole                                             |
|                   | 12   | Green handheld laser        | 1 week     | 4/20     | 7 months   | 16/20    | Full-thickness Macular Hole                                             |
| Zhang (2016)      | 11   | Green laser pointer         | 14 months  | 20/60    | 22 months  | 20/30    | Whitish dots in temporal retina, pigmented scar in fovea              |
|                   | 13   | Green laser pointer         | 8 months   | 20/80    | 21 months  | 20/60    | Dendritic-shaped lesions                                               |
|                   | 8    | Green laser pointer         | 6 weeks    | 20/25    | 6 months   | 20/60    | Dendritic lesion                                                        |
|                   | 10   | Green laser pointer         | 8 months   | 20/25    | NA        | NA       | Dendritic lesion                                                        |
|                   | 14   | Red laser pointer           | 1 day      | 20/80    | 8 days     | 20/80    | Dendritic foveal lesion                                                |
| Zhao (2017)       | 10   | Green laser pointer         | 2 days     | 10/20    | 12 months  | 16/20    | Dispersion disorder of foveal reflex                                  |
| Liang (2017)      | 29   | LED-derived blue laser      | 4 days     | 20/40    | 1 month    | 20/20    | Round red macular lesion                                               |
Xie XY et al. Retinal Lasers

In Oman, three soldiers celebrating a football game developed vision loss after competing in a staring contest with blue-green laser pointers lasting 5-10 seconds[93]. A 2015 Military Medicine case study presented case of “visually significant damage to the retina” from brief handheld laser exposure, and warns of dangers from increasing number of military target designating, range finding and radar warning system lasers with high powers[95]. These and other military-related laser exposure cases are summarized in (Table 1).

Industrial

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) has guidelines for human exposure. Laser Maximum Permissible Exposure (MPE) limits are used in international safety standards. They are based on ICNIRP guidelines, and revised periodically to reflect new technology[104]. Several case reports since 1998 that describe industrial laser injuries including those involving Nd:YAG and Titanium-sapphire lasers and are summarized in Table 2[95,96,97,98,99,100,101,102,103,104,105].

Welders are at risk for retinal injury[106]. In fact, the most frequently reported industrial retinal injuries are from welding arcs and intense lights. However, permanent vision loss from these events are rare. The most frequent attribution for industrial accidents is lack of equipment understanding and failure to follow safety standards[107].

Industrial photoretinitis maculopathy has been described in the following settings: (1) as the result of non-ionizing radiation generated from metal arc inert gas-shielded welding and oxygen lance light[108], (2) despite protective lenses[109,110], (3) in the setting of fluphenazine accumulation in the RPE[111] and (4) due to light flash from short-circuited high-tension electrical circuit[112].

Maximal permissible exposure times are often presented in the field of occupational health for different light sources. For instance, Okuno et al. presented a study of blue-light hazards from various light sources[113], and a systematic analysis was published specifically on light-based insect traps[114].

Pilots

Federal Aviation Administration (FAA) reports of pilot-related laser incidents rose from 2,836 in 2010 to 7,442 in 2016[115]. A 2015 Canadian article analyzed 58 male and 3 female airline pilots who reported to their clinic due to laser strike while flying between April 2012 and November 2014. All pilots reported immediate ocular irritation or light sensitivity, but there were no signs of damage documented on ophthalmic exam that included visual acuity, color vision, visual fields, intraocular pressure (IOP), slit lamp examination, dilated fundus examination, color fundus photos, and OCT[116]. Only 1 confirmed case has been published of permanent retinal injury to a pilot. It occurred from blue laser light while the plane was at an elevation of approximately 396 m. Examination revealed localized photoreceptor disruption on OCT, well-demarcated hypofluorescence on AF, and an identifiable lesion on dilated fundus examination[117]. Despite the lack of lasting ocular damage, these incidents can cause glare, flash blindness and irritation that can jeopardize the safety of the flight.

Commercial

The first commercially available lasers were red (760 nm). Soon, other wavelengths became available to allow for a greater variety of commercial applications. For instance, green lasers are visible in both day and night and good for stargazing and marking far-off targets. Blue and violet lasers reflect a spectrum of colors depending on target properties. Yellow lasers have a gold hue that is desirable for laser guide star in astronomical adaptive optics[118].

Handheld laser pointers sold in the United States have generally been considered safe due to evidence-based Food and Drug Administration (FDA) regulations. However, the online marketplace is unregulated and has resulted in children using them to pop balloons and accidentally injure their eyes[119]. Pointers purchased online are not necessarily readily distinguished by the consumer, or in other cases are marketed to amateur consumers interested in high powered, unregulated lasers[120].

Children are vulnerable particularly to lasers purchased from unregulated marketplaces[121], for instance online, where they can subsequently be used for entertainment[122]. These lasers may be unsafe, over the 5mW FDA safety limit, and indistinguishable in appearance from low-powered lasers. They can produce retinal injury with momentary exposure[123]. Online marketing of these lasers seem particularly attractive to teenagers as fun gadgets, laser swords, and pranks[124].

A variety of retina-involving cases involving commercially-available handheld lasers are summarized in tables 3 and 4. These include lasers purchased overseas and online, cases from Saudi Arabia, China, Japan, Germany, Saudi Arabia, and USA, and incidents involving children shining lasers in a rear-view mirror, creating their own “laser light shows,” an individual passing out at a bar looking at an LED light, ill-advised dares, and accidents[125-143].

Many of the authors made recommendations or suggestions regarding prevention and recognition of laser eye injuries. These include that the presence of outer retinal streaks suggests repeated self-harm as the cause of injury. There is an interesting assertion that although brief exposures to high-powered industrial lasers may be very painful and result in macular holes, less-powered handheld lasers can cause self-injury specifically due to lack of pain and increased duration of exposure[144]. Other authors urge for stricter rules for “uncontrolled and inappropriate use of laser instruments,” and changing the “general misperception that lasers are safe to use for entertainment purposes.”[145]

Certain case reports could not be included in our summary table due to lack of access, language, or formatting difficulty. They are presented here. A 2014 case series from the Netherlands describes boys aged 13, 12, and 9 who developed permanent vision loss after playing with unsafe laser pointers. One of the laser pointers was a class IIIB 5-500 mW, which was purchased while on a vacation in Croatia. Another was a Class IIIA purchased during a father’s business trip in China. The other a class IIIB 5-500 mW laser was purchased in Thailand as a gift[146]. Phototoxic maculopathy has been described from staring at a quartz infrared heat lamp via photothermal and photochemical mechanisms[147]. Tomasso et al. published a 2017 paper in European Journal of Ophthalmology that first described sub-RPE (choriocapillaris) laser pointer injury via findings OCT in a 13-year-old boy who had stared into the beam of a laser pointer[148]. Laser pointers may be used by people with history of self-harm, as in a case report from France in 2016[149].

Recreational

Pseudophakic retinas with polymethylmethacrylat intraocular lenses (IOLs) may be at greater risk due to higher temperature increases and UV retinal irradiances[150]. Modern IOLs, however, are mostly made of acrylic and are designed to block numerous blue and harmful wavelengths. Direct sun gazing is likely harmful, and has been shown in rat models to cause neuronal apoptosis and glio-vascular response in the retina that can lead to permanent vision loss[151]. UV light is a risk factor for age-related macular degeneration (ARMD).
DISCUSSION

Lasers are becoming an increasingly important component of commercial, industrial, recreational, and medical equipment. While lasers are an indispensable component in the management of diseases of the vitreous and retina and have revolutionized the treatment of many ocular conditions, lasers used for non-therapeutic purposes can cause permanent damage and blindness in the eye. With the proliferation of internet sales and cryptocurrencies which are often poorly regulated, lasers are increasingly being distributed without appropriate safety precautions taken, and people are at increasing risk for injury. The eye is particularly vulnerable to laser injury due to the focusing power of the eye and the optical transparency of the eye. Particularly since the retina is central nervous tissue that does not regenerate, this injury is of critical public health importance, especially since many of the people injured in these cases are young and thus will have to live many years with significant morbidity from these injuries. This also highlights the importance and need for further development of therapies that could treat patients who have suffered from retinal laser injury where none currently exist, particular neuro-protective, neuro-regenerative, and stem cell therapies. Continued innovations in laser technology will likely mean that lasers will play an increasingly important and ubiquitous role throughout the world, and thus critical evaluation should also be paid to ensure that non-therapeutic injuries are minimized.

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