

Laser Safety Standards and Measurements of Hazard Parameters for Medical Lasers

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Abstract Laser sources are nowadays largely adopted in medicine and hence they are widespread in medical environment, where patients are present and the users are not always highly specialized in managing laser sources. This has greatly boosted the attention towards safety issues related to exposure to laser beams and to strictly assess the values of well defined laser radiation standard parameters characterizing the level of hazard of laser sources. In this framework, we measured two of the most important parameters, Maximum Permissible Exposure (MPE) and Nominal Ocular Hazard Distance (NOHD), for some of the laser sources mostly employed in medicine. Additionally, we compared our results with data elaborated from standards in order to single out safe and comfortable working conditions. The results here reported have shown that information provided by manufacturers is often not enough to define the hazard level of the laser source and measurements of the main safety parameters are mandatory.

Keywords Laser, Medicine, Laser Radiation Safety Standards, Maximum Permissible Exposure, Nominal Ocular Hazard Distance

1. Introduction

In recent years the use of laser sources have gained attention for an increasing number of new techniques for various applications, including material characterization, quality control of industrial products, study of hybrid systems, sensing, up to medical applications, thanks to the significant advancements in laser source and detector technology and in optical fiber and sample preparation techniques (also including novel nano-object fabrication methods)[1-5]. Among these applications those in medicine are particularly attractive since they are opening the route to new diagnosis or pathology follow up methods along with new surgical procedures[6-9]. Nowadays, lasers are used in surgery, dermatology, gynecology, cardiology, otology, ophthalmology, angioplasty, photodynamic therapy (PDT), and in imaging for diagnostic purposes, just to name some applications. As a consequence of their increasing popularity, laser systems are now highly widespread in medical environment, where they are used also by personnel not highly specialized in optics and laser source management and in the presence of patients. This has greatly boosted the attention towards laser safety issues related to exposure to laser beams and to strictly assess the

values of well defined laser radiation standard parameters characterizing the level of hazard of laser sources[10-12].

Special care has to be taken when considering laser safety in research environment, where lasers are often used in not standard working conditions. In general, to make laser source users aware of laser hazards is crucial for a proper application of rules and safe behaviours even when the working conditions change.

The main hazard due to accidental exposures regards eye injury but it is well known that skin injuries can also occur when high power laser beams are used[13-17]. Safety legislations in Europe and USA take into account non ionizing radiations and laser radiation sources of hazard for human health deriving from physical agents.

Laser safety standards are aimed at: protecting people from laser radiation (180 nm - 1 mm wavelength range) by indicating safe working levels of radiation and by introducing a classification of lasers and laser products according to their hazard degree; clearly defining requirements and procedures for both users and manufacturers and supplying information enabling the adoption of proper precautions; ensuring adequate warning to individuals about hazard associated with accessible radiation from laser products using signs, labels and instructions; reducing the possibility of injury by minimizing unnecessary accessible radiation; giving improved control of the laser radiation hazards through protective features and providing safe use of lasers by specifying user control measures; protecting persons against

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other kinds of hazard resulting from the operation and the use of a laser product as atmospheric contamination, collateral radiation, electrical hazard and fire hazard[13].

Laser safety standards comprise 3 parameters for hazard characterization: the Accessible Emission Limit (AEL), the Maximum Permissible Exposure (MPE) and the Nominal Ocular Hazard Distance (NOHD).

The present paper reports on experimental measurements of two parameters, Maximum Permissible Exposure (MPE) and Nominal Ocular Hazard Distance (NOHD), performed with well assessed methods described in the safety regulation and standards for some of the laser sources mostly employed in medicine. The results are compared with data elaborated from standards in order to single out safe and comfortable working conditions.

2. Biological Effects of Laser Radiation

The interaction between “human tissues” and laser radiation can be described through three mechanisms: photothermal, photochemical and photomechanical interactions. In the photothermal interaction, the absorbed energy of the electromagnetic field is quickly transferred to the molecules thus inducing an increase of the local temperature. When a photochemical effect occurs, the laser radiation makes the structure of molecules vary or form one new molecular specie, or induces a transfer of the energy to another molecule. A photomechanical effect occurs when high-power short pulses are used and produce shock waves that damage tissues during their propagation. These effects mainly depend on the temporal duration of the exposure to radiation along with the temporal regime of the laser (pulsed or continuous), the radiation wavelength and power, and the energy absorbed per surface unit and on the characteristics of the target.

The organs mainly exposed to laser radiation are eyes and skin. The ultraviolet radiation (180 nm - 400 nm) has a photochemical prevailing action causing inflammation of the conjunctiva or, in deeper penetration, cataract. In the skin, dermatitis with possible mutagen effects can occur as a consequence of exposure to high energies. The entity of the damage is determined by exposure time duration and total dose, that is by the absorbed energy per surface unit. Visible (400 nm - 780 nm) and infrared (780 nm - 1 mm) radiation have a thermal prevailing action; the damage derives from the increase of temperature induced in the tissue that can lead, for exposure lasting enough, to protein denaturation. Its entity is therefore determined by the incident radiation power, its duration and the ability of tissue to disperse heat by conduction. For its anatomical configuration the eye is highly vulnerable to the laser light. The ocular damage is particularly elevated when radiation with wavelengths between 400 nm and 1400 nm (visible-VIS and near infrared-NIR) are used since the eye focuses VIS and NIR radiation on the retina, increasing the power or energy

density of one hundred thousand times with respect to incident radiation on the cornea. In medium and far infrared (1400 nm - 1 mm) regions, the thermal effect is limited to the external surface without affecting the retina.

3. Laser Safety Standards and Hazard Parameters

Laser safety standards are usually divided in two parts: 1) prescription of fabrication for the manufacturers and 2) user guide. For designing all the aspects of both parts, three parameters for hazard characterization are used, the above introduced AEL, MPE, NOHD. The AEL indicates the maximum accessible emission level allowed and it is used to categorize laser sources in classes. The classification is strictly necessary for safety standards since lasers sources can present hazard levels strongly varying with emitted radiation characteristics, such as wavelength, power and temporal behaviour (continuous wave emission, pulsed emission), repetition rate, etc.. Such classification is carried out considering the power level of emission and the wavelength of laser radiation. The manufacturer must consider all the working possibilities of the laser system and adopt the appropriate classification. According to the IEC (International Electro-technical Commission) standard (IEC 60825-1)[16] lasers are grouped in 7 classes of hazard depending on the AEL value: 1, 1M, 2, 2M, 3R, 3B and 4, the lowest degree of hazard corresponding to class 1 lasers and the highest to class 4 lasers. Recently, US Food and Drug Administration (FDA)'s Center for Devices and Radiological Health (CDRH) has decided to accept certain conformance standards of IEC 60825-1 and IEC 60601-2-22 standards in lieu of those required by 21 Code of Federal Regulations (CFR) §1040.10 and §1040.11. This FDA recognition of the IEC standards has not yet been codified and in the interim, so as to reduce the regulatory burden on industry and the CDRH agency, FDA has released ‘Laser Notice No.50’ that explains which of the IEC standards will be accepted in the USA. This industry guidance allows some IEC standards for lasers to be accepted within the USA[18]. Hence, since 2007 FDA has accepted the new classification labelling.

The AEL is usually a maximum power (in W) or energy (in J) that can be emitted in a well defined spectral range and exposure time that passes through a specific aperture set at a specific distance.

The MPE represents the radiation level to which people can be exposed without suffering harmful effects, i.e. for which there is a negligible probability for creating damage under the worst case conditions. It can be expressed as radiant exposure H ($J m^{-2}$) or irradiance E ($W m^{-2}$). The MPE value is fixed by the International Commission on Non Ionizing Radiation Protection, ICNIRP[16,19], and represents the maximum level of irradiance for a given type of laser source to which eye or skin may be exposed without suffering short or long term damages. Since the damage

depends on optical and thermal properties of the material hit by radiation (skin or eye) which, in turn, are different depending on the radiation wavelength, MPE table values specific for eye and skin are defined. To refer to these two tables is absolutely mandatory in the spectral region of retinal damage (400 – 1400 nm)[6-8]. Additionally, the level of damage depends on the exposure time. In this frame, the use of radiant exposure or irradiance represents the best choice for evaluating the hazard of a laser source, a very simple relationship between E and H holding: $E=H/\Delta t$, Δt representing the pulse duration.

The NOHD is "the distance from the source where the radiation is equal to the Maximum Permissible Exposure". Therefore, somebody staying at distances from the source greater than the NOHD is in a low risk zone, where the radiation turns out to be equal or smaller than the admitted MPE limit. Conversely, an operator staying at distances less than the NOHD is in a dangerous zone, sometimes called nominal hazard zone. This parameter must be estimated with the aid of IEC 60825-1 (and obviously by using the ANSI Z.136-1) standards and through experimental measurements that have to be carried on following protocols defined by the standards. To calculate the NOHD is obviously meaningful only when the laser irradiance or power is higher than the MPE, in order to define a safe region.

To understand how to calculate the NOHD it could be useful to recall that the irradiance E at a given distance R from a laser source is given by the following expression:

$$E = \frac{4P_0 e^{-\mu R}}{\pi(w_0 + R\phi)^2} \quad (1)$$

This formula assumes a Gaussian beam with a power P_0 , an intensity diameter w_0 (in m) at its waist, a beam divergence ϕ (in rad), and an extinction coefficient μ due to atmosphere absorption. P_0 is the maximum power for a laser emitting a continuous wave radiation or the averaged power for a pulsed laser. ϕ and w_0 are measured at the 1/e point of the beam profile, according to the hypothesis of a Gaussian beam. In practice, some approximations have to be considered. The hypothesis of a Gaussian beam is strictly verified only for gas lasers; in the other cases multi-mode beam structures have to be taken into account. At this aim, if considerations are done about the laser power, P_0 is usually increased by a multiplicative factor (2.5); otherwise the radiant intensity has to be considered instead of the power. R can represent 1) the distance between the apparent source and either the observer or 2) the entrance aperture of the measurement system or the distance between the apparent source and the diffusing target. The effect of atmospheric attenuation (quantified by the term $e^{-\mu R}$) can be commonly neglected since μR is very small for most purposes and, then, $e^{-\mu R} \approx 1$. The factor $R\phi$ is also usually very small and can be neglected in many cases, too. In our analysis we will keep the latter term and neglect the exponential one. In this frame, in order to evaluate the NOHD, we replaced R by the NOHD and E by the MPE in Eq.1, and solved the obtained expression with respect to NOHD:

$$\text{NOHD} = \frac{\sqrt{4P_0 / (\pi \text{MPE})} - w_0}{\phi} \quad (2)$$

which is a general expression. When a lens is used to focus the laser beam and is considered as an internal part of the laser system, the NOHD has to be evaluated by using the following expression instead of the one given in Eq.2

$$\text{NOHD} = \frac{f \sqrt{4P_0 / (\pi \text{MPE})}}{d} \quad (3)$$

where f is the focal length and d is the diameter of the beam on the lens.

4. Materials and Methods

In this study we focused the attention on the most popular (continuous-CW and pulsed-PL) lasers used for medical applications. In particular, we selected the two most used gas laser sources, namely He-Ne and Argon lasers, along with Er-YAG, Ti-Sa and semiconductor solid state (SSSC) lasers[1,6,20-22]. Er-YAG laser is used for laser resurfacing of human skin, for removing warts and in oral surgery, dentistry, implant dentistry, and otolaryngology. SSSC lasers are widely used in dermatology and Ti-Sa lasers are used in medical imaging. We measured irradiance from He-Ne (Model 05-LHP-151, Melles-Griot, USA), Argon (Model Sabre, Coherent, USA), Ti-Sa (Model Mira 900, Coherent, USA), Er-YAG (Deka, Italy) and SSSC (Model PLP02, Hamamatsu Photonics, Japan) lasers. Their main characteristics (namely, wavelength of emitted radiation $-\lambda$, nominal power $-P_{\text{nom}}$, repetition rate $-F$, pulse duration $-\Delta t$, beam diameter on the lens $-d$, beam divergence $-\phi$) are shown in Table 1.

Table 1. Main Characteristics of the Investigated Laser Sources

Laser Sources	λ (nm)	P_{nom} (W)	f (Hz)	Δt (ps)	d (mm)	ϕ (mrad)
He-Ne	633	5.0 10^{-3}	CW	CW	0.80	1
Argon	457- 514	25	CW	CW	2.1	0.30
Ti:Sa	800	2.5 1.4	CW $76 \cdot 10^6$	CW 0.150	0.7	1.70
SSSC	824	$5 \cdot 10^{-4}$ $5.4 \cdot 10^{-6}$	CW $1 \cdot 10^6$	CW 30	2.0	$\parallel 25^\circ$ $\perp 30^\circ$
Er:YA G	2940	3.5	14	$450 \cdot 10^6$	1	5

The experimental setup employed for the measurements (shown in Fig.1) was realized in order to simulate and measure the irradiance produced by the direct exposure of a certain tissue to the laser beam. It was mainly composed by the laser source under investigation, a circular diaphragm

that simulates the pupil or a portion of the skin, a detector (power meter Model 3A, Ophir Optonics, Israel) to measure the power of the portion of the beam passing through the diaphragm and by a focalization lens to use when the spot emerging from the diaphragm is greater than the diameter of the detector opening [14-17].

The minimal distance adopted for irradiance measurements was kept equal to the accommodation distance for human eyes that is nearly equal to 10 cm. The diaphragm diameters can be set in the range from 1 to 11 mm depending on the wavelength and the tissues. Given these characteristics, diaphragm diameter aperture (A) values were selected for each laser and operating condition, according to the safety standards, in order to perform measurements for evaluating the hazard level for eye (A_{eye}) and for skin (A_{skin}).

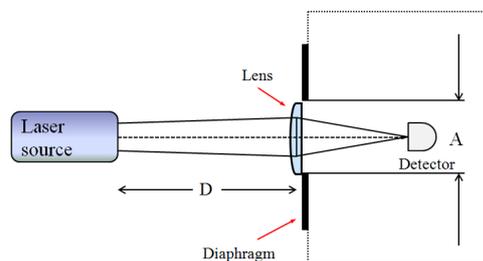


Figure 1. Experimental apparatus for irradiance measurements. D: Measuring distance; A: Diaphragm diameter aperture

For each investigated laser and operating condition the MPE values for eyes (MPE_{eye}) and skin (MPE_{skin}) were calculated according to the safety standard tables. Under the safety regulations, a laser is considered to work in continuous emission (CW) regime when it emits continuously for a duration equal to or greater than 0.25 s. Accordingly, in our calculations an emission duration of 0.25 s (corresponding to the time of palpebral reflex that limits the eye time exposure to this value) was considered for CW lasers operating in the visible part of the spectrum (where the reflex acts). For lasers that emit outside the visible spectrum, an emission duration of 10 s was considered to be potentially dangerous. According to regulations, for lasers operating in pulsed regime (PL) the MPE value was calculated by considering the most restrictive among the following conditions: a) the MPE from a single pulse within a train of pulses does not exceed the MPE for a single pulse; b) the average exposure for a complete pulse train (of constant amplitude) during a time interval ΔT shall not exceed the MPE values for a single pulse as given in the standard; c) the average exposure from all the pulses within the pulse train does not exceed the MPE of a single pulse, multiplied by a correction factor. This correction factor is a function of the number of pulses (N) that are expected during the exposure period (ΔT). In mathematical terms, this becomes: $MPE(\text{train}) = MPE(\text{single pulse}) N^{-0.25}$. This correction factor is only applicable when the pulse duration is less than 0.25 seconds; for any longer durations, it is presumed that the two MPE

values are the same. As one can see, the average $MPE(\text{train})$ will be less than the MPE of the single pulse. Performing calculations for all the PL lasers and all the conditions, it came out that the most restrictive criterion is the one adopting the exposure to a train of pulses with a total exposure equal to 10 s. In the presently examined cases we considered the direct exposure to the laser beam without considering the occurrence of extended source viewing conditions, given the characteristics of laser sources here analysed.

After the numerical evaluation of the MPE values, the beam power was measured for each laser source and operating conditions at specific distance (D) and for a proper value of w_0 by employing the set-up shown in Fig. 1. For all the sources allowing two operating conditions, both CW and PL regime were considered. Additionally, in order to account for the dependence of the parameter on the laser power, measurements at different powers have been carried out for the Argon laser. The measured irradiance E (W/m^2) was obtained by dividing by the diaphragm area ($S = \pi[A/2]^2$) the average beam power measured when the laser-diaphragm distance is equal to 10 cm.

Table 2. Hazard Class, A_{eye} , A_{skin} , MPE_{eye} and MPE_{skin} of the Investigated Lasers

Laser Sources	Hazard Class	A_{eye} (mm)	A_{skin} (mm)	MPE_{eye} (W/m^2)	MPE_{skin} (W/m^2)
He-Ne	3B	7	3.5	25.5	1956
Argon	4	7	3.5	25.5	1956
Ti:Sa (CW)	4	7	3.5	16	3100
Ti:Sa (PL)		7	3.5	16	3160
SSSC (CW)	1	7	3.5	18	3500
SSSC (PL)		7	3.5	18	3540
Er:YAG	4	1	3.5	996	996

5. Results and Discussion

The MPE values as calculated from both eye and skin safety tables (MPE_{eye} and MPE_{skin} , respectively) for the properly selected diaphragm aperture A (A_{eye} and A_{skin} , respectively) are shown in Table 2 along with the hazard class of each laser source. The obtained MPE_{eye} values indicate that He-Ne and Argon lasers have the same damage threshold. Nearly the same happens for Ti:Sa (working in CW) and SSSC lasers. All these lasers can be responsible for damage to retina. The highest MPE_{eye} value is obtained for Er:YAG laser indicating that this is the less dangerous laser for eyes since its radiation is mainly absorbed by the cornea and the vitreous humour and does not reach the retina. On the other hand this laser is the most dangerous one for the skin since the emitted radiation is absorbed by skin external layers causing a relevant thermal damage. This results in its MPE_{skin} value, which is the lowest one. For these peculiar characteristics the Er:YAG laser has $MPE_{eye} = MPE_{skin}$. For

the other lasers the radiation deeply penetrates the skin and thus undergoes a larger thermal dispersion.

Table 3. Experimental Values of Laser Power and Irradiance and Calculated NOHD and OD Values for the Investigated Laser Sources in Eye Safety Conditions. The Experimental Values are Affected by an Error < 4%

Laser Sources	w ₀ (mm)	P _{meas} (W)	E _{eye} (W/m ²)	NOHD (m)	OD
He-Ne	7	7.65 10 ⁻³	198.80	19	0.89
Argon	7	0.570	14.7 10 ³	475	2.76
		1.092	28.8 10 ³	662	3.05
		1.712	44.5 10 ³	830	3.24
		2.432	63.4 10 ³	991	3.40
Ti:Sa (CW)	7	3.245	84.3 10 ³	1144	3.52
		1.09	28.3 10 ³	174	3.25
Ti:Sa (PL)		0.936	24.3 10 ³	160	3.18
SSSC (CW)	7	0.46 10 ⁻³	12.1	-	-
		4.7 10 ⁶	0.1	-	-
Er:YAG	3.5	0.97	100.8 10 ³	0.40	2.00

As for the measurement of eye safety parameters, the values of power (P_{meas}) and irradiance (E_{eye}) for all the laser sources are shown in Table 3 as obtained with the reported w₀ and at D=100 mm. The experimental values reported in the table are affected by an experimental error < 4%. Both P_{meas} and E_{eye} (E_{eye}=P_{meas}/S_{eye}, see Materials and Methods section) have been reported in the table in order to enable a direct comparison with the corresponding MPE_{eye}, shown in Table 1. By doing the comparison, it comes out that E_{eye} experimental values are greater than MPE_{eye} values for all the investigated lasers except for SSSC one. Hence, the NOHD for He-Ne, Ti:Sa, Argon and Er:YAG lasers has been calculated by using Eq.3 and reported in the table. The obtained NOHD values (see Table 3) greatly differ from one laser to another, confirming that information provided by manufacturers is not enough to define the hazard level of the laser source and measurements of the main safety parameters are required. Argon and Ti:Sa lasers are very dangerous also at high distances (>175 m) from the source, even when they are not working at their highest power levels, as shown by the values obtained at the different power values considered for the Argon laser. This evidence confirms the hazard level associated to the use of laser sources belonging to class 4. In the case of an Er:YAG laser source used in working conditions (including the use of a collimating lens) proper to dentistry applications, the NOHD is about 40 cm notwithstanding this source belongs to class 4; this is mainly due to the use of the collimating lens placed at the end of the bundle.

It has to be recalled that the conditions of total safety are obtained when all the operators and patients are at a

distance > NOHD. If operators and patients are in this zone, no safety prescriptions are given. If somebody has to stay at distances < NOHD, he/she must wear eye protectors (goggles)[23] specific for the wavelength and the laser operating mode. An important characteristics of the goggles is their Optical Density (OD). The proper OD of the goggles to be used is dependent on E_{eye} and MPE_{eye}, according to the following expression

$$OD = \log \frac{E_{eye}}{MPE_{eye}} \quad (4)$$

The OD value has been calculated using Eq.4 for all the investigated lasers with E_{eye}>MPE_{eye}. The corresponding values are reported in Table 3. They fall in a wide range (0.89-3.52), the highest value is obtained for the Argon laser set at 3.2 W working power.

Regarding the evaluation of the parameters for the case of the skin safety, the measured values of power (P_{meas}) and irradiance (E_{skin}) for all the investigated laser sources are shown in Table 4 as obtained with w₀=3.5 mm and at D=100 mm.

Table 4. Experimental Values of Laser Power and Irradiance for the Investigated Laser Sources in Skin Safety Conditions. The Experimental Values are Affected by an Error < 4%

Laser Sources	P _{meas} (W)	E _{skin} (W/m ²)
He-Ne	7.64 10 ⁻³	793.56
Argon	0.570	59.25 10 ³
	1.094	28.8 10 ³
	1.705	44.5 10 ³
	2.435	63.4 10 ³
Ti:Sa (CW)	3.228	84.3 10 ³
	1.09	28.3 10 ³
Ti:Sa (PL)	0.936	24.3 10 ³
SSSC (CW)	0.46 10 ⁻³	12.1
SSSC (PL)	4.7 10 ⁶	0.1
Er:YAG	0.97	100.8 10 ³

As the experimental values reported in Table 3, also the experimental values reported in Table 4 are affected by an error < 4%. Also in this case, to have shown both P_{meas} and E_{skin} (E_{skin}=P_{meas}/S_{skin}, see Materials and Methods section) allows us a direct comparison between experimental irradiance and MPE_{skin} values, reported in Table 2. From this comparison it is evident that Argon, Ti:Sa and Er:YAG laser sources, all belonging to class 4, are dangerous for skin. In fact, at the measuring conditions here considered (see Table 2) all the measured E_{skin} values are higher than the MPE_{skin} ones and hence the use of protective devices is mandatory to work in these conditions. For such lasers some cautions have to be taken also in presence of ignitable materials to avoid fire. On the contrary, He-Ne and SSSC lasers are not dangerous for skin.

6. Conclusions

In the present paper the safety standards for non ionizing radiation have been applied to evaluate the hazard level related to laser sources widely used in medicine. In particular, the accidental exposure to direct radiation has been considered and the MPE values have been calculated using the tables that are available in the safety standards for eye and skin. The radiant exposure has been experimentally measured for different kinds of lasers belonging to class 1, 3 and 4. Well assessed methods described in safety regulations and standards have been used to underline the efficacy of such methods in safety issues. The results have shown that information provided by manufacturers is not enough to define the hazard level of the laser source and measurements of the main safety parameters are required. Additionally, it has been shown that the AEL, MPE and NOHD parameters have to be correctly managed by the users in order to define and adopt the right individual protection devices and behaviours. Moreover when lasers of class 3B or 4 have to be used safety standards recommend to address to a Laser Safety Officer (LSO), with specific competences in order to verify the respect of the standards and to supply adequate information to the staff on the hazard situations. An experimental assessment of the hazard parameters and the comparison with those of reference from safety standards turns out to be useful in order to estimate the residual hazard that can be still present after applying all the engineering protection and administrative rules.

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