VOLUME 4 | ISSUE 2

Medical Physics ORIGINAL ARTICLE

A preliminary investigation on the occupational exposure to laser radiation in Greece

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SUBMISSION: 11/1/2019 | ACCEPTANCE: 05/04/2019

ABSTRACT

Purpose: The term optical radiation refers to the ultraviolet (UV), the infrared (IR) and the visible regions of the electromagnetic spectrum. The relevant occupational exposure legislation, Directive 2006/25/EC, employs limits and Occupational Health & Safety (OHS) regulations for laser (coherent) and non-coherent artificial optical radiation (AOR). Lasers are widespread mainly in health care facilities, industry, cosmetology applications, research and entertainment installations. The harmonisation of the safety approach is challenging.

Material and Methods: The Directive has been transposed to the Hellenic legislation, containing all its requirements. However, there is no sufficient progress towards the Directive's practical implementation, mainly concerning the conducting of the required integrated risk assessment by qualified experts (namely: Laser Safety Officers-LSOs) and the overall safety management of the laser installations. The measurements of the appropriate optical quantities are a vital part of the risk assessment and reveal technical difficulties, therefore assumptions have to be made about the way the laser beams may reach (mainly) the eye; the procedures, the geometry and the involved materials imply specific exposure/accident scenarios for each assessed workplace.

Results: Measurement results from cosmetology, research laboratories and a material processing industry revealed safety gaps, identifying overexposures not only for the "obvious" primary beam's exposure; scattered beams implied by the installation's geometry were also above the limits. The training of the personnel was also found to be poor.

Conclusions: The detected misapplication of the overall laser safety procedures justifies the need for detailed investigation and future actions by the involved Authorities.

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KEY WORDS

Laser safety; Directive 2006/25/EC; Occupational health and safety (OHS); Laser safety officer (LSO)

Introduction

The use of laser devices in health care facilities (ophthalmology, refractive surgery, photodynamic therapy, dermatology, scalpel, vascular surgery, dentistry), industry (cutting, welding, marking, drilling, photolithography), cultural heritage and art restoration, metrology (distance measurement, surveying, velocimetry, vibrometers, electronic speckle pattern interferometry, optical fiber hydrophones, high speed imaging, particles sizing), cosmetology and physiotherapy applications, education and research, optical information storage (CD/DVD, laser printers) and communications, holography/spectroscopy, as well as in entertainment installations (laser shows and pointers) is widespread. However, the laser safety approach demanded by the legislation and/or relevant standards is not integrated and in many cases not even activated; a claim sustained due to the lack of relevant references. Recently, even ultra-fast pulsed lasers have been developed under optimistic transnational projects involving fusion, or the production of ionising particles that could be used for proton cancer treatment [1].

In any laser application field, hazards may be either considered immediate, having to do with the laser device, or indirect, having to do with the specific application. Immediate hazards are correlated, for example, with the electrical parts of the laser device (capacitor's discharge, electrocution, sparks, explosion, fire) and with toxic gases produced from the cryogenics liquids or from the active materials of the laser [2]. Indirect hazards involve the emission of dangerous substances (e.g. operating theatre air contamination with fumes from tissue ablation and charring) [3], the ignition of explosive substances (like medical gases), fire or exposure to secondary radiation, but mainly the potential eye and skin exposure to the direct and to the scattered laser beams [2, 4-5]. Every potential hazard can eventually lead to an accident as several related reports on a worldwide basis testify. For example, 50 years after the discovery of the laser, the Laser Institute of America (LIA) reported the distribution of 50 years' accidents (1960-2010) per installation [6]. For the first 25 years, the incident reports involved mainly accidents of scientists in laser development and operations, while for the next 25 years, the vast majority of them involved medical application-related accidents, revealing the growth of this sector. Furthermore, 7974 accidents involving eye (69%) and skin damage (11%), injuries of the involved technicians (21%), and scientists (17%), but also of doctors, nurses, patients, students, spectators and light show operators, were also recorded in the Rockwell Laser Incident Database (1964-2010) [7]. Additionally, a number of reports point out the necessity of recording, classification, training by official agencies, availability and use of personal protective equipment (PPE), evaluation and re-evaluation of laser systems [8-10], but without explicitly making reference to specific laser safety measurements.

The recent European Directive 2006/25/EC employs limits and Occupational Health & Safety (OHS) requirements for laser and non-coherent artificial optical radiation (AOR-solar exposure is excluded), for the human eyes and the skin, based on the International Commission of Non-Ionising Radiation Protection (ICNIRP) AOR guidelines (see below). Optical radiation (OR) is part of the electromagnetic spectrum and includes the ultraviolet (UV), the visible (VIS) and the infrared (IR) regions. The Directive (2006/25/EC) has been transposed to the Hellenic legislation (P.D. 82/2010) without substantial changes, and in this study it will be referred to as "the Directive". This Directive is a specific one of the OHS framework European Directive (89/391/EEC), including all the main OHS protection approaches.

Briefly, the undesired photobiological effects (that also form the basis of their therapeutic/diagnostic applications [11]) may include: i) mainly photochemical and thermal damage of the eye, erythema and cancer for the skin, as far as the UV region is concerned; ii) photochemical and retinal damage of the eye and thermal damage of the skin, as far as the VIS is concerned and iii) eye and the skin thermal damage, as far as the IR region is concerned [12]. Even if adverse eye and skin health effects are potentially possible across the entire optical spectrum, the risk of retinal injury in the VIS and near IR regions (400 to 1400 nm) is of particular concern and some related changes have been introduced on the initial ICNIRP guidelines [13].

However, after the first years of its implementation, the

Table 1. The first page of the applied checklist

Laser Safety Checklist Date:__________

Comments

Company/lab:__________

Laser system:__________

Use of the Laser system:__________

Laser Category: 1 1M 2 2M 3R 3B 4

Operating Voltage: ________ Cooling: YES NO

Operating Environment: Temperature:_____ Humidity:_____

Laser Beam / Output

Laser operation : CW - Pulsed Energy Output:______

Pulse Duration:______ Δt Between Pulses:______

Frequency:______

Safety	Comments
Danger Signs: Yes - No	
Secured Area of the laser system: Yes – No	
Protection Cover: Yes – No	
Hazard Switch: Yes-No	
Light Condition: VG – G – M – P – VP	
Protective glasses: Yes – No	
Protective for Skin: Yes – No	
Reflective Surfaces: Yes – No	
System/Machine Modification: Yes - No	

Directive received criticism regarding its complexity (for example, advanced mathematical formulation and challenging applicability), not only on the part of non-coherent radiation, but also concerning laser radiation [14]. Additionally, poor progress has been made towards its practical implementation, regarding the conducting of the required integrated risk assessments by appropriate qualified experts; the appropriate measurements are completely missing. This highly specialized OHS gap prompted the OHS Directorate of the Hellenic Ministry of Labour (the Ministry is the Authority in charge for the verification of compliance with the Directive's requirements), the University of Thessaly and the National Technical University of Athens (NTUA), to try to investigate the extent of occupational laser exposure safety procedures, conducting safety measurements.

Material and Methods

The OHS assessment experience accumulated from the related EMF [15] and non-coherent AOR [14] fields was used to explore the laser light safety issues; some of them are: i) its unique physical characteristics; ii) the enormous extent of applications; iii) the potential power of some lasers and the consequent hazards they imply, which are sometimes bigger than the ionising radiation [16]; iv) the difficulty to quantify hazard parameters (i.e. geometry, exposure/accident scenarios and measurements); and v) the lack of an overall nationwide safety management, which reveals that the laser hazards are often underestimated or even neglected. In this sense, initial laser safety assessment was performed in representative large-scale sectors, such as cosmetology, research labs and industrial material processing, through appropriate checklists developed on the basis of OHS principles and regulations (**Table 1**) [17]. Aspects under investigation included laser classification, nominal output, pulse characteristics, beam diameter, temperature, humidity, lighting conditions, safety training and controls, appointment of a Laser Safety Officer (LSO), implementation of protective measures etc. Most of all, the challenging issue was the development of exposure/accident scenarios (that is the possible way the laser beams may reach mainly the eye), the conducting of the appropriate optical physical quantities measurements and the identification of the distances over which the optical radiation hazards exist.

Laser classification is an initial beam hazard safety measure that takes into account the output of the laser devices, as well as the human access to their light emission, grouped into seven classes: 1, 1C, 1M, 2, 2M, 3R, 3B, and 4, whereas the higher the class, the bigger the potential to cause harm [9, 18]. The installations tested were of classes 3B and 4, as these imply high intensity open beams and thus higher risk.

The exposure protection limiting system of the Directive contains several Exposure Limit Values (ELVs) that, apart from the laser power emission, depend on the wavelength, the exposure time, the pulse duration and the spot size [19]. The physical quantities used to express ELVs are: i) the irradiance or power density (E: Wm^{-2}); ii) the radiant exposure (H: Jm^{-2}) and iii) the (integrated) radiance (L: $Wm^{-2}sr^{-1}$) [16]. The applicable ELV for the tested installations is the radiant exposure, H (J/m^2) and is used in conjunction with correction factors, like C_A, C_B, C_C and C_E, given in table 2.5 of Annex II of the Directive. The aforementioned approach, as already stated, comes from the ICNIRP's guidelines [13].

At some distance from the laser source, as the beam diverges, the irradiance will equal the eye ELV. This distance is called the NOHD (nominal ocular hazard distance) or equivalently, NOHA (nominal ocular hazard area) [19] and must be identified by appropriate signaling [16, 18]. This

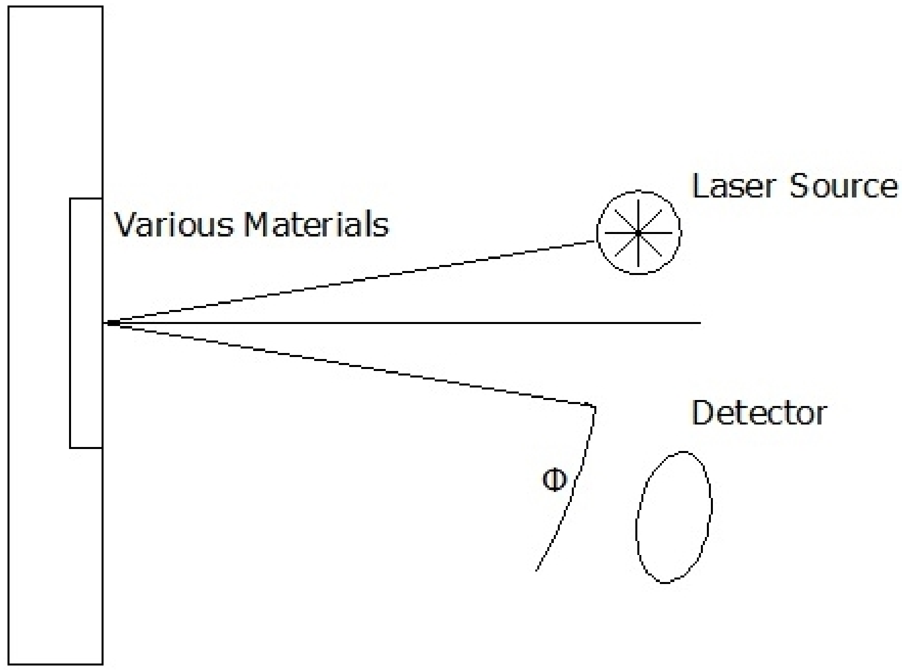

Fig. 1. *Experimental set-up for the tabulation of the angular distribution (φ) of the scattered/reflected beams for various materials in a research lab. The φ values start from the catoptric reflection (φ=0) and increase corresponding to diffuse reflection.*

distance is either provided by the manufacturers or can be calculated, for Gaussian or quasi-Gaussian beams, by **Equation 1**:

$$NOHD = \frac{\sqrt{\frac{4\times radiant\ power}{\pi\times ELV}} - initial\ beam\ diameter}{beam\ divergence} \qquad \text{(Equation 1)}$$

These parameters usually come from manufacturers' data: radiant power (W), initial beam diameter (m), ELV (W/m^2), beam divergence (radians) [18].

Laser safety issues and measurements

Safety procedures are implied not only by OHS principles, but also by many laser safety standards [18]. However, there is no clear and practical code of practice, as the lack of references indicates [16].

An initial risk evaluation for laser systems includes [18]: i) sources that don't pose any significant hazard (using laser classification and the NOHD); ii) exposure scenarios as well as an assessment of which of them needs further attention; iii) exposure assessment, against ELVs, if needed; iv) multiple sources exposure; v) actions to be taken in case the ELVs are exceeded; vi) recording of the significant conclusions. Corrective actions escalate from engineering and administrative controls to personal protective equipment (PPE) [9, 18, 20].

The workplaces' selection criteria, on the basis of an initial safety assessment of the presented survey, were: i) wide use of high intensity open beams; ii) reports of accidents; iii) not sound background of the involved personnel on laser issues.

The measuring equipment comprised of various digital hand held (model: Vega, company: OPHIR, probe: 30A-P-SH-V1, range 1mV-30W, pulse and single shot mode) and oscilloscope driven energy meters, special laboratory oscilloscopes (LeCroy 9361 Dual 300 MHz Oscilloscope), digital photometer (Gossen Mavolux digital) and hand held thermohydrometer (Testo 610), all of them properly calibrated according to the requirements of the laboratories [16, 21].

Since no one expects to be intentionally exposed to the primary laser beam (nevertheless this possibility cannot be entirely excluded), the most common exposure case involves indirect exposure to the reflected/scattered beams; exposure scenarios are installation specific.

Temperature and relative humidity were also measured when possible, due to their proper laser system function dependence. Finally, the ambient lighting conditions were

Fig. 2. *A double head Nd:YAG industrial laser system. The energy meter is seen in the front-left side of the picture.*

also measured since they are directly related to the dilation of the eye's pupil and thus to potential retinal hazard; adequate lighting conditions are reported to be about 500 Lux (normal office) [21].

Cosmetology

Cosmetology can be considered as part of the medical sector laser applications, whose exposure scenarios are really challenging and need detailed investigation.

An Nd:YAG hair removal system (Fotona, FIDELIS xp) was tested. Apart from the main (invisible) laser beam at near IR, 1064 nm, the system was also equipped with an additional red (650 nm) tracer beam. The system's specifications were 10 W mean power, 10 ms pulse duration, 1 Hz repetition rate and 4 mm beam diameter. The performed measurements and the exposure scenario involved only the primary laser beam (1064 nm), indicating a potential misuse. The eye ELV is given by **Equation 2** and the respective one for the skin by **Equation 3** [18, 19]. For the applied wavelength and pulse duration characteristics, arises that $C_C=C_E=1$ and $C_A=5$.

$$H_{eye}=90\cdot t^{0.75}\cdot C_C\cdot C_E \ (J/m^2) \qquad \text{(Equation 2)}$$

$$H_{skin}=1.1\cdot 10^4\cdot C_A\cdot t^{0.25} \ (J/m^2) \qquad \text{(Equation 3)}$$

Research lab

An Nd:YAG research lab-made (at the NTUA) laser system of various nominal outputs, 6 ns pulse duration and 1 Hz repetition rate, was tested. Scattered beams scenarios for three different materials (wafer, blacked plexiglas and anodised aluminum) were developed and their angular distribution was tabulated. In this respect, several issues like the reflecting materials' characteristics and the overall geometrical arrangement of the installation were taken into account; more specifically, due to diffusion, many scattered beams were considered (**Fig. 1**).

The eye ELV is given by **Equation 4** and the respective one for the skin by **Equation 5** [18, 19]. The applied wavelength and pulse duration characteristics imply that $C_C=C_E=1$ and $C_A=5$.

$$H_{eye}=5\cdot 10\text{-}2\cdot C_C\cdot C_E \ (J/m^2) \qquad \text{(Equation 4)}$$

$$H_{skin}=200\cdot C_A \ (J/m2) \qquad \text{(Equation 5)}$$

Industry - material processing

A vivid, solar heater construction industry was assessed. The main laser installation was a double-head 1064 nm Nd:YAG (**Fig. 2**) (TRUMPF HL 506P 500W average power), 500 W mean power, 2.4 J pulse energy, 0.3 ms pulse duration and 155 Hz repetition rate. The eye and skin ELVs are giv-

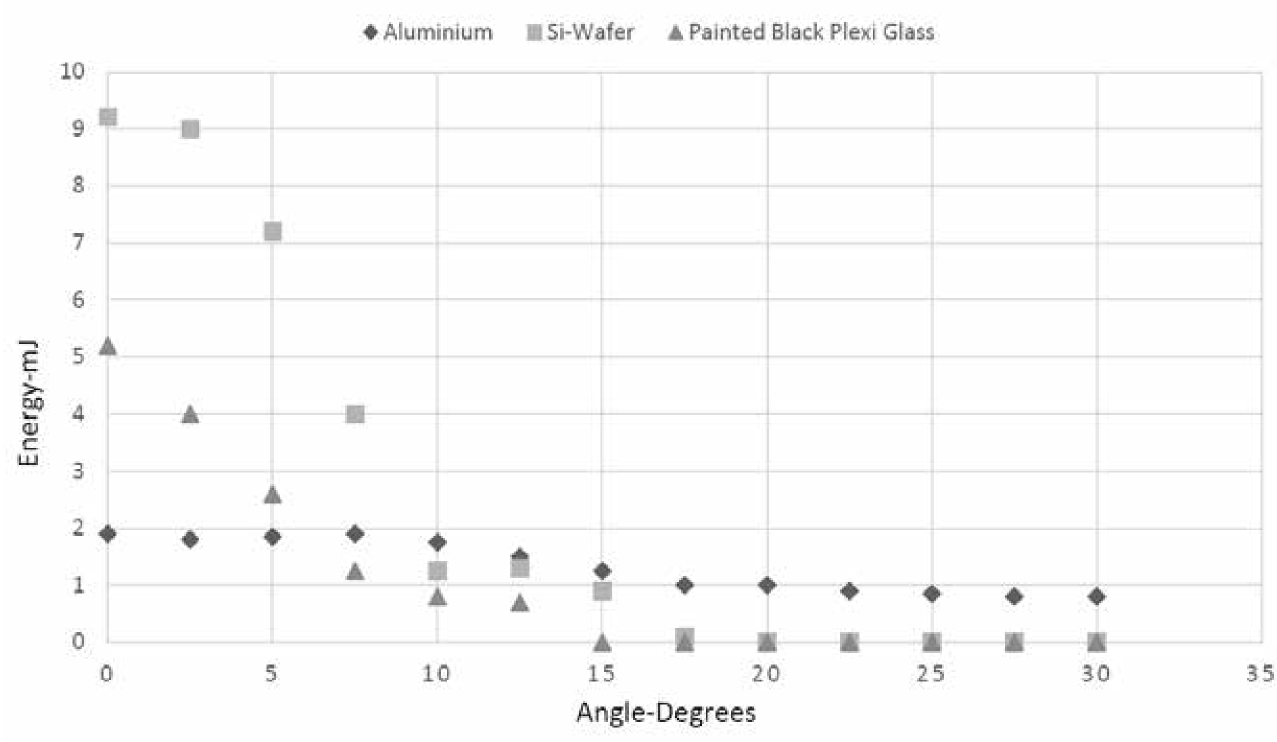

Fig. 3. *Measurements results of the scattered beam's energy (mJ), for different angles from catoptric reflection and for three different materials in a research lab.*

en by Equations 2 and 3 above. Due to the double-head laser system geometry - it moves fast along the welding area - only the reflected/scattered beams at the opening of the safety curtain were measured; that is the most realistic exposure case scenario.

Results

Cosmetology

The nominal 15 J/cm2 primary beam's output was verified to be 14.9 J/cm2. Consequently and apart from the safety procedures, a verification of the laser functional characteristics, that is a kind of Quality Assurance (QA), can be performed. These values correspond to approximately 52000 and 8.5 times over the eye and skin ELV per pulse respectively (Equations 2 and 3: $ELV_{eye}=H_{eye}=0.506\ Jm^{-2}$, $ELV_{skin}=H_{skin}=9780\ Jm^{-2}$). Concerning safety, there was no warning signalling, no protective curtains and window covers, there were a lot of reflecting and/or transmitting surfaces around. Safety glasses of the appropriate optical density (OD) were available, but no protective gloves. There were no appointed LSO and no reported OHS personnel training (**Table 2**).

Research lab

Primary beam's output was verified to be 120 mJ and 126 mJ using two different oscilloscope driven energy meters; beam's area was adjustable by a lens focus system and thus no nominal output was available. Concerning safety, warning signalling was present but no protective curtains, a lot of reflecting surfaces were around and some kind of interlocks were available. Safety glasses with the appropriate OD were available, but they weren't used, and no protective gloves were available. There was an appointed LSO who had conducted personnel training, but the lab was also used for studying, setting the need for advanced safety assessment (**Table 2**). The environmental conditions reported were: humidity 55%, temperature 27°C and ambient lighting 250 Lux. The angular distribution of the three materials' reflected/scattered beams, after their primary beam irradiation, was recorded (**Fig. 3**): The NOHD for the worst case scenario, which is catoptric reflection at φ=0° (**Fig. 1**), was calculated to be approximately 2 m. The safety distance for diffuse reflection (i.e. greater φ values) was calculated to be approximately 0.6 m.

Table 2. Summary of the availability of the basic laser safety procedures in the assessed workplaces. PPE stands for personal protective equipment (i.e. glasses and gloves)

Safety procedures	*Workplaces*		
	Cosmetology	*Research lab*	*Industry*
Risk assessment	NO	NO	NO
Appointment of LSO	NO	YES	YES
Warning signalling	NO	YES	YES
Protection curtains	NO	NO	YES
Warning lights	NO	NO	YES
Emergency buttons	YES	NO	YES
Interlocks	NO	YES	NO
Availability of eye PPE	YES	YES	YES
Availability of skin PPE	NO	NO	NO
Use of PPE	NO	NO	NO
Personnel training	NO	YES	NO
Lighting (Lux)	200	250	200

Industry

The worst exposure result ranged up to 25 times over the eye ELV and 0.1% of the skin ELV, revealing great fluctuation. The environmental conditions reported were: humidity 38%, temperature 29°C, lighting 200 Lux. Concerning safety, certain solutions were active: warning signalling, protective curtains, warning lights (**Fig. 4**), emergency buttons, PPE (OD>7) and the employer was the appointed LSO. But there were no interlocks, metallic reflecting surfaces were abundant, the personnel didn't make PPE use and the risk assessment was pending (**Table 2**).

Discussion

The current study was initiated aiming to identify occupational laser exposure, but also to raise the need for OHS. The enormous extent of laser applications, even if the exact

Fig. 4. The protective curtain of the industrial installation with its opening, through which all measurements were conducted. Signalling and warning light are visible.

numbers in Greece are missing, and the first measurement results reveal a demand for enhanced attention concerning an integrated safety approach. The survey is numerically limited, but the results are considered as the first step in order to open up the challenging field for the interpretation of the Directives' ELVs and the application of measurements.

The individual in charge to apply the OHS in practice is the Safety Officer (SO) whose main OHS tool is the risk assessment; the scientific approach to identify and quantify hazards (legislatively speaking though, the main responsibility lies with the employer). The upgrade of this "general" SO to a dedicated LSO, especially for certain laser installations, is a demand. An official and sound accreditation agency (or authority) that will safeguard LSO accreditation is an OHS issue of great importance.

Late in 2015, an evaluation of the Directive's practical implementation was reported at EU level, concluding that the AOR Directive appears to attract more diverse and extreme views than most of other EU Directives, with clearly no consensus over its need and value [14, 16]. However the findings presented in this survey, despite the worldwide lack of laser safety measurements, set a sound basis to approach laser OHS through primary and reflected/scattered beams exposure scenarios, safety checklists, measurement of the appropriate optical quantities and the identification of safety distances and procedures. Especially for the scattered beams, their angular distribution for different materials was recorded in a research lab, revealing the crucial factor of geometry for the determination of possible accidents; reflected beams have a rare, but still present, justified possibility to reach target organs and cause harm.

The detected safety assessment procedures revealed gaps. Some of the reasons that hazards were underestimated or even neglected (**Table 2**) seemed to be the lack of: i) an appointed LSO; ii) approved OHS engineering controls (protective housing, enclosures, interlocks, delayed operation switches, warning lights, audio signals, remote controls, alignment aids, attenuators, shutters, viewing and filtered windows, elimination of reflections, access prevention and emergency stops); iii) administrative controls (documentation of the safety management, local rules, checklists, controlled area specifications, safety signs and notices); iv) training of the personnel; and v) periodic laser parameters measurements, as part of an integrated risk assessment. Moreover, while the last OHS action step, the appropriate PPE, was present at the site, its actual use, which is of critical importance especially at distances below the NOHD, was not ensured.

The measurement of the appropriate optical quantities under the development of realistic exposure scenarios, imitating potential accidents, was the most challenging part of the survey, as dedicated equipment had to be used without an available code of practice and the appropriate ELVs had to be assessed.

For the cosmetology application, findings confirmed the initial estimations according to which in a "small" installation it is less possible to recognise and respect safety rules. In the case of the primary beam scenario, the eye's overexposure to ELV was calculated to be many thousands of times greater than the established limit and, even if this seems an exaggerated scenario, it reveals the degree of the potential hazard. Apart from that, skin's overexposure to ELV was also detected. Though this may be considered as an expected side effect of the required treating cosmetology procedure, it is still undeniably an occupational hazard. Overall, the safety procedures were found to be very poor; by way of illustration it should be stated that large reflecting/transmitting surfaces were present in the area of activity, a fact that strengthens the impression that the primary beam's potential enormous overexposure was neglected. No scattered beams assessment was conducted, since this would require real life conditions involving the actual treatment of a person, which at this stage was not an objective.

For the research lab application it was made possible to create different reflected/scattered beams exposure scenarios. It is important to keep in mind the wavelength dependence of the materials' reflectivity, meaning that a surface could be "dark" in a spectral range or highly scattering in another. It was quite astonishing that the worst case approach gave a hazard distance (NOHD) of 2 m and the quite more realistic one a hazard distance of 0.6 m, meaning that safety glasses must be worn at all times when the lasers are active; other activities, such as studying, are not to be held in parallel without precautions. Many safety procedures, starting from the appointment of a competent LSO and his corresponding actions, were active but the results reveal that there is more to be done (i.e. risk assessment, protection curtains, warning lights, etc.).

The most powerful installation assessed, the industrial one, revealed the most active safety procedures, justifying the feeling that "big" installations are set in a way that ensures safety. Apart from that, in this case, the system's geometry ensured relatively low exposures. Nevertheless, as a rare exposure scenario, specific overexposure was measured, right at the opening of the safety curtain, indicating that even if this risk is very low, it actually exists for very specific angles. Despite that, the available safety glasses were not used by the personnel, revealing the need for laser hazards training. Such training, along with the conducting of an integrated risk assessment, constitute two important tasks of an LSO. Measurements are the active part of this risk assessment, which are both a legislative demand and a means for the inspection Authorities to confirm compliance with the OHS requirements. The above considerations are further reinforced by the fact that, since the Directive's release, the ICNIRP has lowered the limit of Equation 4 by more than a half [17], meaning that the potential overexposures detected are more than two times higher than the reported ones.

Maintenance procedures and especially laser system ones are of high risk. Even class 1 systems could be hazardous under maintenance and the identification of the relevant exposure assumptions is challenging, meaning that what has to be assessed is the specific procedures of the installation in total.

Findings reveal the need to activate and improve safety procedures in laser applications; the 2006/25/EC Directive is applicable. The role of the LSO has to be improved beyond the appointment of a "general" SO. His activation can raise issues such as personnel training, written instructions, appropriate signalling, interlocks, specification of the NOHD, proper selection, maintenance and prompt PPE use. The LSO accreditation is a major open issue that has to be treated in terms of an overall laser safety management strategy. The overall laser safety legislative upgrade is under consideration, but what is rather more important now is the activation of the present legislative and OHS practices and tools. Many low cost solutions, like the ones detected for the low lighting conditions, are applicable. Systematic recording of laser accidents and of near misses, another LSO competence, will reveal the real situation and prompt neglected safety procedures.

Future work and major concern in order to map occupational laser exposure, is to assess medical lasers and real time treatments, as they are reported to be the most hazardous late laser era installations; sample risk assessment and QA protocols are of first demand. The investigation of the vague laser entertainment field is also of major priority.

Acknowledgements

We would like to thank Prof. M. Makropoulou (NTUA), I. Tsilikas (NTUA), Dr. E. Xontzopoulos (owner and LSO of the industrial laser installation), Dr. N. Merlemis (Technological Educational Institute of Athens), Dr. C. J. Hourdakis and Dr. Z. Thrapsanioti (Licensing and Inspection Department, Greek Atomic Energy Commission) for their crucial contribution, and once again Mrs. Triantafyllia Totou for being so kind to make substantial linguistic improvements. R

Conflict of interest

The authors declared no conflicts of interest.

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Gourzoulidis GA, Boursianis T, Maris TG, Sianoudis I, Achtipis A, Stasinopoulou P, Kappas C. A preliminary investigation on the occupational exposure to laser radiation in Greece. *Hell J Radiol* 2019; 4(2): 1-10.