LASER PHYSICS ELEMENTS TO CONSIDER FOR LOW LEVEL LASER THERAPY

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A brief review is made about the properties of the laser radiation, with particular emphasis on their importance in low level laser therapy. An important part of this section is dedicated to the properties of the laser beams emitted by the semiconductor lasers (laser diodes or diode lasers) given the broad use of such lasers in low level laser therapy. The basic elements about the laser beam interaction with the tissues are introduced in close connection with the penetration depths of the laser beams into the target tissues. A general scheme of a medical laser equipment is introduced, according to the author's experience, insisting on the requirements which result from the need to deliver to the medical doctors friendly, easy to use laser medical equipment. The simple formula used to compute the doses for tissue exposure at laser radiation with specific comments dedicated to the low level laser therapy applications are introduced. Lasers and laser medical products classes are introduced in connection with the laser safety rules to be considered while using the products for therapy applications. The practical rules recommended for the safe use of medical laser equipment are specified based on the author's experience and recommendations for room arrangement and instrument selection in medical praxis related to the laser medical applications are given. The laser safety practical rules for the patients and the medical personnel are specified in direct connection with the current laser medical applications.

Key words: Low Level Laser Therapy, LLLT, Laser Medical Equipment, Exposure Doses, Laser Safety Rules, Laser Classes, Laser Products Classes.

Properties of laser radiation

The laser is a source of electromagnetic radiation with particular (special, distinctive) properties. Summarizing these properties one may distinguish: monochromaticity, coherence, low divergence (very good directivity), brightness and other related properties.

Monochromaticity

The monochromaticity is that property of the laser radiation which describes its spectral distribution correlated with its intensity. So, in the laser beam case the maximum intensity is obtained at a given wavelength around which the most part of the radiation is emitted; the most part of the beam energy is accumulated at a small number of wavelengths around the wavelength of the maximum intensity. The laser beam intensity drops to zero very fast at wavelengths other than the wavelength of the maximum; this property is often described as the high spectral purity of the laser beam.

In other terms one speaks about the narrow spectral width of the laser beam, much narrower than in the case of classical optical sources.

One may understand these characteristics starting from the stimulated emission process and from the amplification of the stimulately emitted radiation in the optical cavity; the systems which constitute the laser active medium are emitting at the same wavelength with the radiation which induces the stimulated emission and which originates from the initially spontaneously emitted radiation reflected along the resonator optical axis. The amplification is the highest at one wavelength which is the wavelength of the single longitudinal (axial) mode accepted by the optical cavity.

In general, this means that if the gain in the laser cavity is greater than the losses in the same cavity within a continuous spectral band centered on the emitter's resonance line λ_0, only the axial modes are amplified which are compatible with both lineshape of the active medium and positive gain. Experimentally, a given number of axial modes may be amplified, but if a particular design of the optical cavity is made, only one of them will be above threshold and will dominate the laser emission. It is possible that the single longitudinal (axial) mode be accompanied by supplementary axial modes which are decreasing in intensity with the distance on the wavelength scale from the maximum of the main line. If one considers the total number of such adjacent lines the envelope which describes best the laser beam intensity distribution with the wavelength is a Lorentzian curve; it is much more intense than the natural emitted line on the expense of a narrower width than this one, but larger than the single axial laser line[1].

On the other hand, one has to take into account that the monochromaticity properties of the laser radiation are present within its spatial distribution and consequently within the resulting divergence of the laser beam. If transverse electromagnetic modes are amplified by the optical resonator, for a given transverse mode which has a given spatial distribution one may have several longitudinal

(axial) modes of the same spatial distribution but with different wavelengths. These modes are spaced on the frequency scale (and consequently have different corresponding wavelengths) with ν_F.

Practically, the width of the laser line is described by its full width at half maximum (FWHM) $\Delta\omega_{Laser}$, given by [2] :

$$\Delta\omega_{Laser} \sim (8h\nu/P_{out})(\Delta\omega)^2 \qquad (1)$$

where ν is the laser radiation frequency, $\Delta\omega$ is the emitter's (atomic) energy level width and P_{out} is the output power of the laser beam. Typically, for a laser beam emitted in the visible, a line width of 10^{-1} - 10^{-3}nm is not very difficult to obtain. With the price of loosing in intensity a laser radiation of 10^{-4}nm or some orders of magnitude lower may be obtained.

For the LLLT applications, the monochromaticity of the laser radiation is not a critical parameter. This is due to the fact that the dominating interaction process between the laser beam and the tissue is the absorption ; the absorption bands of the target tissues are broad (of the order of some nanometers) so that there is no need to have an extremely spectrally narrow laser beam or even a very stable wavelength of the output laser beam.

Coherence
The coherence is one of the most specific and powerful properties of the laser radiation and is intimately related to the stimulated emission mechanism through which the laser radiation is obtained.

The electric field $\vec{E}$ of the laser beam is described by a function such as:

$$\vec{E}(\vec{r},t) = \vec{E}_0(\vec{r},t) \exp[i(\omega t - \vec{k}\,\vec{r})] \qquad (2)$$

where $\vec{r}$ is the vector which defines the position of the point in which the laser beam arrives, t is the time moment at which the observation takes place, $\vec{E}_0$ is the maximum value the electric field may reach in the considered point, ω the electrical field angular frequency, $\vec{k}$ the so-called wave vector of the beam and $i = \sqrt{-1}$. According to equation (2) in a given point, at the distance $\vec{r}$ from the laser source, the electric field may oscillate sinusoidally between two maximal values ($-E_0$ and E_0), having a constant angular frequency ω ($\omega = 2\pi\nu$) at any time moment t. The reason for which, in describing the coherence properties (and more generally, the optical properties) of the laser radiation the component electrical field is chosen is that the optical phenomena are related to the electrical field component which is part of the electromagnetic field. So, the laser beam intensity is given by $\left|\vec{E}\right|^2$, its polarization state is described by the polarization of the electric field only, etc.

The coherence property of a laser beam is described by its capability to determine the appearance of interference fringes when interacting with a second laser beam emitted by the same laser at the same wavelength. One may define two types of coherence:

a) Spatial coherence
In this case two laser beams originating from two different points (which may be located at smaller or higher distances within the laser beam cross section) of the same laser beam are interfering when superposed in the same point, producing interference fringes; the laser source is characterized then by the spatial coherence and the laser beam is called spatially coherent.

Generally, in most lasers the axially emitted light leads to stimulated emission and the laser beam has a finite, well-defined cross section around the optical axis of the optical cavity. The spatial coherence shows the dimensions of the transverse surface within the cross section of the laser beam inside which the electric field of the laser radiation $\vec{E}(\vec{r},t)$ is described by the same equation (2). In the laser case the whole cross section of the laser beam is characterized by the same $\vec{E}(\vec{r},t)$ or otherwise saying it is formed by a single wave plane; the spatial coherence of the laser beam is total. The spatial coherence has direct consequences on the laser beam divergence and focusing.

b) Temporal coherence
This property is characterized by the fact that the laser radiation emitted from a certain point of the laser source at a given moment interferes with the laser radiation emitted from the same point at a later moment, provided both beams are incident in the same point. The time interval within which the interference may be obtained is called "coherence time" and the laser is defined as a temporal coherence source of radiation. The coherence time is in fact the time length of the wave train, i.e. the time interval ? t within which the radiation is described by the same electric field $\vec{E}(\vec{r},t)$ given in eq. (2). Starting from the coherence time one may define the coherence length of a laser beam which describes the spatial length of the laser wave train, i.e. the length within which the interference phenomena may be obtained. The coherence length and the coherence time may be measured with a Michelson interferometer mounted in a lambdameter arrangement [3].

In a cw laser the coherence time is longer than in a pulsed laser case. Typical values of the coherence time in cw laser are in the 10^{-7}s - 10^{-2}s range which leads respectively to coherence lengths of 30m to 3×10^6m.
The temporal coherence of the laser beam described by the coherence time is responsible for the interference effect obtained during this time in a given space zone

when superposing two laser beams emitted by two lasers of the same type at the same wavelength. This makes one of the most important differences between the laser sources of light and the classical (uncoherent) sources for which such an effect may be obtained only for beams originating from the same single source.

Directivity

The directivity is the property of the laser radiation to be confined within a beam which is propagating in space so that its cross section is practically not modified at small distances (of the order of some meters). The directivity is correlated with the divergence property of the laser beam which describes its angular spreading and is measured in mrad (milliradians). The directivity describes qualitatively the property of the laser radiation to remain concentrated at long distances along and around a given direction; the divergence describes the same properties quantitatively.

The spatial distribution and consequently the divergence of the laser beam depend on the geometry of the optical cavity and on the shape of the laser active medium. If the resonator mirrors are plane parallel and infinite in dimensions only axial modes are amplified and the transverse spatial effects in the active medium and the resonator may be neglected.

In the experimental arrangements and the laser construction solutions spherical mirrors are used, as the plane/plane resonator is very sensitive to mechanical misalignments, with finite dimensions (a typical diameter of such a mirror is between 20mm and 50mm). This fact modifies the divergence of the laser beam increasing it and determines the appearance of the transversal modes which are coexisting with the longitudinal (axial) modes.

In the general case, the spherical mirror resonator allows to obtain a finite number of transverse electromagnetic modes which are usually denominated by $TEM_{l\,m\,q}$. The pair (l, m) defines a transverse mode which has a corresponding space distribution. Some examples of different transverse modes which are obtained in real working conditions are shown in Fig.1; the (0,0) transverse mode characterizes the Gaussian beam. As may be observed in Fig.1, l shows the number of dark spaces in the laser beam cross section between the spots on horizontal and m shows the same number on the vertical [4].
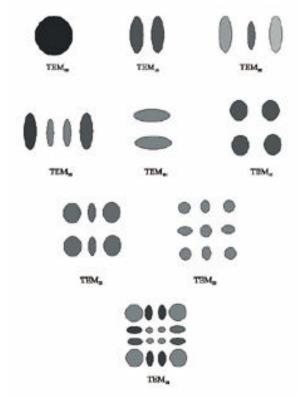

Fig.1 Transverse mode structure of laser beams

For a given pair (l, m) the index q shows the number of compatible axial (longitudinal) modes having the same spatial distribution, but different frequencies; the separation on the frequency scale between the longitudinal modes is $v_F = c/(2d)$ (c is the speed of light and d is the spacing between the resonator's mirrors) regardless of the l and m values. The transverse modes which are not overlapped may originate in different spatial regions within the laser active medium so that they could coexist without competition between themselves (i.e. at relatively equal intensities).

If the propagation of the laser beams is considered in space, the transverse mode structure determines the shape of the beams shown in Fig. 2.
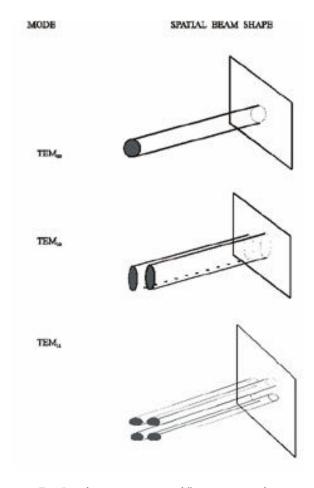
MODE   SPATIAL BEAM SHAPE

TEM₀₀

TEM₀₁

TEM₁₁

Fig.2 Laser beams in propagation at different transverse mode structure

In considering the directivity and divergence characteristics of the laser beams one should always take into account their mode structure. This becomes more important since the divergence may be different from one mode to another and usually two or more modes may coexist. When the divergence characteristics of a laser type are specified one usually considers TEM$_{00}$ (Gaussian) mode which may be extracted from the laser.

Even for Gaussian mode case the real laser beam is more or less close to an ideal Gaussian, exhibiting different kinds of asymmetries if studied from the point of view of the beam propagation[1].

As a concluding remark one has to stress that although the real laser beams exhibit better directivities and much lower divergences with respect to the classical light sources are far from perfect optical beams so that extensive care has to be taken to correctly handle, process, transmit and use them in LLLT applications.

Brightness
In qualitative terms, the brightness of the laser radiation is described by the laser light beam intensity which is given by the number of photons emitted outside the laser optical cavity, reported to the unit surface of the laser beam cross section . The laser beam brightness is due to its directivity

coupled with its power and with the monochromaticity of the radiation.

So, a beam power of 60W cw in the laser case means 60W optical power spread on a cross section of some millimeters diameter at practically the same wavelength or along a spectral range some tenths of nanometers wide around a given wavelength (color). This is enough to cut even some metals. The same power emitted by a classical source means the optical power emitted in 4π solid angle at different wavelengths along a wide spectral range. This is the case of an electric bulb.

In other words only a part of the number of photons emitted inside the optical cavity leaves the cavity to generate the laser beam outside the cavity. This part is controlled by the transmission coefficient of the extraction mirror belonging to the optical cavity; this coefficient should be chosen function of the laser active medium characteristics in order to make a compromise between the gain inside the laser active medium and the losses within it taking into account the needed output from the optical cavity.

The brightness of the laser beam is one of its properties due to the high power density (W/m²) or energy density (J/m²) found in a cross section through the laser beam. Starting from it, the speckle properties of the laser radiation are noticed and studied.

Polarization
The polarization is a nonspecific property of the laser radiation as any electromagnetic radiation has given polarization properties. It is particularly important to know the polarization state of the laser beam since it coexists with the other specific properties of the laser radiation.

While discussing about the mode structure of the laser radiation, the TEM$_{l\ m\ q}$ modes were introduced. The radiation emitted in each (l, m, q) mode may have two independent orthogonal polarizations which makes it possible to consider each polarization correlated with an independent oscillating mode.
In the spherical mirror resonator due to its circular symmetry the two polarization modes at the same pair (*l, m*) have the same spatial distributions. If the optical cavity and the laser active medium have equal gains and losses for both polarizations the laser beam will contain simultaneously two independent modes of equal intensity. The laser beam is in this case unpolarized.

If one of the polarization states is better accepted by the laser active medium and the mirrors of the optical cavity, the polarization state of the laser beam may be linear. The polarization state could also be controlled by introducing a polarizer inside the optical cavity.

Laser diode beam characteristics

Due to the fact that the semiconductor lasers (laser diodes or diode lasers) are commonly used in laser therapy in the following the characteristics of the beams emitted by such lasers are treated.

For the LLLT purposes the elliptical cross section of the laser beam and the laser diode intrinsic astigmatism are often perturbing factors in practical irradiation of tissues. The elliptical cross section of the beam is the result of the rectangular shape of the semiconductor laser cleaved facets. This leads to the fact that the laser beam may not be entirely collimated, allowing only its quasi-collimation.

According to wave optics, the beam output from a small aperture has in a particular direction a full divergence angle θ given by:

$$\theta = 4\lambda/\pi d \qquad (3)$$

where λ is the laser beam wavelength and d is the size of the emitting laser active medium facet in that particular direction.

For a so-called index-guided laser diode, at low power level due to the dx size of the active medium along the Ox direction (which is typically 5μm) and dy size along the Oy direction (typically 1μm) the divergence angle on Ox, θ_x and on Oy, θ_y are such that

$$\theta_y \sim 3\theta_x.$$

In Fig.3 are shown both θ_x and θ_y and the elliptical cross section of the laser beam in this case; the back (totally reflecting) facet of the laser active medium and the front emission facet are also shown. The third dimension dz of the laser active medium is shown, which is usually around 150μm.
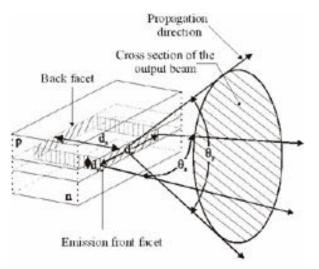

Fig.3 Laser beam characteristics emitted by a semiconductor laser

Generally, an acceptable characterization of the divergence properties for all types of laser diodes is very difficult to do since there are important differences between two major types of laser diodes, namely index-guided and gain guided and more than that the laser diodes have individualistic behavior, regardless of the type.

The ratio between θ_y and θ_x is not consistent even if two laser diodes of the same type are compared, so that the elliptical cross section of the laser beam varies from one laser diode to another. This characteristic is important in LLLT applications since it describes the shape of the laser beam used for therapy and the evolution of its dimensions with distance; this has direct implications on the variation of the laser beam energy density with distance and consequently the variation of the doses to be applied on the patient with distance.

For the divergence of a laser beam emitted by a laser diode one may define a beam divergence (parallel) θ_{II} as the full angle at half of the peak intensity in the laser beam profile parallel to the junction plane. The beam divergence (perpendicular) $\theta_\perp$ is the full angle at half of the peak intensity in the laser beam profile perpendicular to the junction plane.

The typical values of the laser beam divergence are θ_x ~7deg, θ_y ~ 20deg.

Astigmatism

The astigmatism is another result of the rectangular front facet of the semiconductor laser (Fig.4).

In principle, the beam emitted from a small dimensions facet is equivalent to a beam emitted by an imaginary point source P whose position can be located by tracing the beam backwards. In Fig.4, such a point P_x (which is the origin of the beams emitted in the horizontal plane) is located behind P_y (which is the origin of the beams emitted in the vertical plane) because dx is higher than dy and consequently θ_x is smaller than θ_y. The larger dx and the narrower dy, the bigger the difference between θ_x and θ_y and the higher the distance between P_x and P_y.

This behavior of the semiconductor laser beam is called astigmatism and the distance between P_x and P_y is its numerical description.

Practically, this means that when using a single aspheric lens to collimate the laser beam this may be achieved only in one direction, either on Ox or on Oy since the points P_x and P_y may not be placed at the same time in the focal point of the collimating lens. The diode laser beam astigmatism has an important role in LLLT since it controls the beam collimation limits and alternately, if needed, the dimensions and the shape of the focus obtained with an optical system which process the laser beam for therapy purposes.
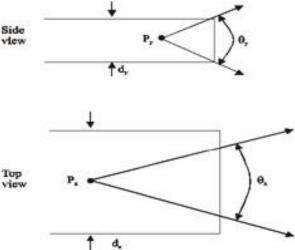
Fig.4 The astigmatism of the laser beam emitted by a diode laser

Fig.5 Semiconductor laser beam output power dependence on the injection current.

At the same time this astigmatism is important to consider when the diode lasers are used to optically pump other types of lasers such as solid state ones.

Laser beam optical output power

The laser beam power or laser beam optical output power is an essential characteristic of each laser beam. For a diode laser emitting under injection current conditions, the forward current intensity may be varied typically, for the lasers used in LLLT up to about 100mA cw. One may define the current intensity threshold I_{th} below which the laser diode emits like a LED (uncoherent light emitting diode) and above which laser light is produced (Fig.5). From Fig.5 it results that the output optical power is strongly dependent on the injection current values above threshold, much stronger than the optical output power dependence in the LED case.

A value of the maximum forward current tolerable under continuous operation I_F (Fig.5) which produces a P_0 laser beam optical power may be defined as the sum of I_{th} and a specified current for each laser diode type; above this value the laser diode may be most probably damaged and the output may drop drastically. The laser beam output power P is measured in watt. If the laser operation is made in pulsed regime one may define an average output power P_a which may be written as:

$$P_a (W) = Pp (W) \times \Delta\tau(s) \times f(s^{-1}) \qquad (4)$$

where Pp is the power per pulse expressed in watt, $\Delta\tau$ is the pulse time width and f is the pulse
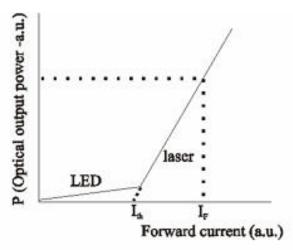
repetition rate expressed in Hz. If a laser diode is used emitting in pulsed regime pulses of 200ns time width at a repetition rate of 1kHz, the power per pulse being 10W, the average beam power will be 2mW. For each laser pulse one may define a peak power / pulse, which is the maximum output power emitted at a moment within the pulse duration. In this case the laser pulse time shape can be reasonably approximated with a triangle whose basis is the total pulse time width; the peak power is the power corresponding to the peak of the triangle.

Monochromaticity of the diode laser beam

The laser radiation is in the semiconductor laser case not a simple TEM_{00} mode or even a TEM_{pq} mode; the optical bandwidth of the laser beam is higher than in gas lasers and multimode (longitudinal) oscillations are produced unless special care is taken to emit only single longitudinal modes[5]. The spectral purity of the oscillating modes in a diode laser tends to be worse than in the gas lasers, but still better than the resolution of the most classical instruments (monochromators). The separation of the single longitudinal multimode operation from the longitudinal multimode operation may be made by choosing the reflection coefficents of the active medium facets and by adjusting the semiconductor temperature and injection current. A typical spectral bandwidth of a single longitudinal mode is of the order of 10^{-1}nm; the spectral range covered by the multimode structure is at worst around 5×10^{-1}nm.

These typical monochromaticity characteristics for a diode laser are not extremely important in LLLT since the absorption bands of the biomolecular systems within the body structure are large enough to allow the resonant absorption in the tissue. Though, an important feature is the energy distribution of laser beam in its cross section since this should assure the uniform exposure of the tissue to the laser light.

Coherence

The coherence of the laser beams emitted by the diode lasers is defined in terms
of the interferometric observable fringes produced in an interferometer when two beams originating from the same initial laser beam are superposed. The laser beam coherence length is defined as the longest difference between the arms of an interferometric system in which the laser beam is introduced, at which sufficient interference fringes with the necessary contrast may still be obtained. The approximate formula of the coherence length, l_c, is:

$$l_c = c/\Delta\nu \text{ or } l_c = \lambda^2/\Delta\lambda \qquad (5)$$

where c is the light speed, $\Delta\nu$ is the bandwidth of the laser beam expressed in frequency units, λ is the wavelength of the laser radiation and $\Delta\lambda$ the spectral width of the laser beam expressed in wavelength units. If λ = 500nm and $\Delta\lambda$ = 0.25nm it results an l_c = 0.2mm which is typical for a semiconductor laser. More generally, the coherence length of the laser beam emitted by a diode laser is usually of the order of at most some millimeters[3]. The influence of the coherence properties of the laser beams in LLLT is still the object of a systematic study.

Basic elements about the laser beam interaction with the tissues

Laser medical applications are covering a large variety of research and development activities which is summarized along the main lines in TABLE 2.1

TABLE 2.1 Laser applications in medicine

Medical applications of lasers
* Low Level Laser Therapy (LLLT)
* Laser surgery
* Laser Photodynamic Therapy (called usually PDT)
* Laser in vivo diagnostics
* Laser applications in laboratory medicine
* Basic research

As far as the medical applications are concerned (the term "medical" covers here what other authors name "laser applications in medicine and surgery") the irradiating dose is one of the most important parameters to consider while applying the treatment.

Physical processes characterizing the laser beam penetration into the tissue

If a laser beam incident on a tissue is considered, there are several processes which may describe the coupling of the laser beam with the tissue and the laser beam interaction with the tissue itself. In Fig.6 is shown a collimated laser beam of I_0 intensity incident on the patient skin (or at the tissue surface); the processes to be described are the same if the beam is focussed although their contributions to the energy balance between the incoming beam on the tissue and the outcoming beam may be different. At the contact with the skin (tissue limit), a part of the beam is reflected (I_R) according to the geometrical optics lows and another is backscattered ($I_{b.s.}$). This means that a part of the laser beam is sent back to the medium the laser beam comes from (in most cases air) without really interacting with the skin or the tissue. For a better coupling between the laser radiation and the tissue these losses should be minimized by properly cleaning the skin to decrease its reflection coefficient at the used laser beam wavelength and to diminish the skin light scattering properties. If the interaction takes place with a tissue which belongs to an open wound the reflection coefficient could be minimized by controlling the level of the liquids within the wound.

These losses are, in total, usually not higher than 5% from the incoming beam power and depend also for the skin on its quality, pigments, etc.

Inside the skin or the limiting surface of the wound the beam is absorbed ($I_{a.s.}$) and suffers also other processes (refraction, scattering, etc) which may be neglected from the point of view of the energy balance. Once in the tissue, the laser beam is refracted (I_r) function of the tissue optical properties, changing its propagation direction with respect to the incident beam. A part of the beam is forward scattered ($I_{f.s.}$), spreading the light around the incidence point inside the tissue in all directions, function of the unhomogeneities of the tissue. Another part (I_a) is absorbed by the tissue atomic and/or molecular components by the so-called resonant interaction between the laser beam and the tissue. Finally, it remains an I_{rem} beam
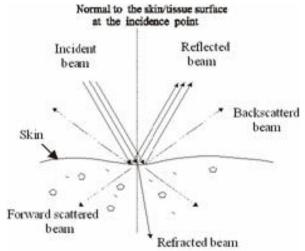

Fig.6 The main processes characterizing the laser beam propagation in the tissue.

intensity which is function of the deepness at which the light intensity is measured in the tissue. Energetically, the balance is given by:

$$I_0 = I_R + I_{b.s.} + I_{a.s.} + I_r + I_{f.s.} + I_a + I_{rem} \qquad (6)$$

One should mention that I_r means here the intensity of the beam which suffered only refraction down to the observation plane; the same is true for $I_{f.s.}$, I_a and I_{rem} so that each term in the right member of the equation is the complement of the others.

The absorption of the laser radiation in the tissue is due mostly to the hemoglobin and water[6] but a relatively important contribution have also the melanin and the oxyhemoglobin. It results that to have a deeper beam penetration in the tissue one should use the "window" between approximately 600nm and 1.5? m where the two major tissue components (hemoglobin and water) absorb less than 5% from the incoming radiation. At wavelengths lower than 600nm the hemoglobin becomes the most important absorber while above 1.5? m the water dominates the absorption; if one intends to have a deeper penetration of the beam in the tissue one should use a beam wavelength in the 600nm – 1.5? m spectral range..

In a more general plane when one speaks about the penetration of the light beam in the tissue or through the skin, one should take into account that usually the light emitted from a classical source is considered i.e the light characterized by low energy densities; the laser beams have, at the same wavelengths, power (energy) densities higher with orders of magnitude so that the penetration depths are higher due to the greater number of photons available in the laser beams[7].

Following the absorption of the laser radiation, function of the beam power level and of the wavelength there are two kinds of processes which may take place:
a). Reversible processes which are of interest for LLLT.
b). Irreversible processes which are of surgical interest; these may be produced in real time or, as in photodynamic therapy, in a given time interval

Generally, the power levels recommended for the medical applications are as follows:
- –μW, for diagnostics purposes in order not to perturb the tissue.
- mW – hundred mW for LLLT.
- W – tens of watt (function of the wavelength and the tissue characteristics) for surgical purposes.

After absorbing the beam one may have as one of the most important consequences the heating of the tissue. For LLLT purposes the laser beam-tissue interaction should be performed so that the tissue temperature should not exceed 45 °C.

The effects produced by the laser radiation on the tissue may be controlled also by focusing the laser beam on the skin or near it. In Fig.7 are shown three possible positions of the laser beam focus with respect to the skin (tissue) surface; the focus region is not a point, neither has the shape and dimensions of an ideal geometrical figure, due to the imperfections of the laser beam which is incident on the focusing optical system. If the focus is centered on the tissue surface one may have a larger energy transmitted to the body on a smaller surface area (usually not more than some square millimeters). If the power density is of the order of
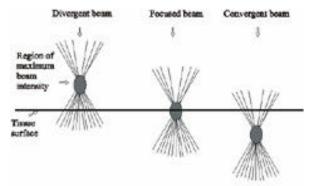

Fig.7 Different positions of the laser beam focus with respect to the skin (tissue surface)

some mW/mm² one may produce effects without irreversible modifications in the tissue.

When the laser beam falls divergently or convergently on the skin (tissue) the effect on it may be controlled function of a larger number of irradiation parameters such as: power (energy) density, irradiation time, beam wavelength and polarization, etc.

General scheme of a laser medical equipment.
In this chapter are introduced the basic data about the requirements for a laser medical equipment. The basic idea of a laser medical equipment design should be that the physician has to pay the main attention to the patient and the laser beam interaction with the tissues of interest and only in a small extent to the equipment itself. So, the equipment should be conceived to work either under manual or under computer on-line control, the laser subunit being automated locally or emitting under computer control [8].

In the equipment structure a LASER RADIATION INITIAL PROCESSING is usually included which allows filtering (spectral or spatial) of the laser beam, controlling the transmission of it by using a shutter and/or focusing of the beam on the input of the LASER BEAM TRANSMISSION UNIT . This unit may consist of an opto-mechanical coupler (1 in Fig.8) which is a subunit which contains several totally reflecting mirrors mounted within a flexible arm so that the emergent radiation keeps a constant propagation direction regardless the movement, the position and the shape of the arm. This

kind of transmission system is used for the laser radiation having a wavelength for which there are not optical fibers available, such as 10.6? m - the CO_2 laser radiation wavelength. A more convenient solution is to use an optical fiber (2 in Fig.8) for wavelengths distributed in UV, visible and near and middle infrared; in this case the flexibility and the volume covered by the emergent head of the fiber is higher with respect to the opto-mechanical solution and even the losses in the beam energy/power are smaller. The usual length of the LASER BEAM TRANSMISSION UNIT is at most 3m. The output head of this system may be free, i.e. may be manipulated directly by the physician to interact with the patient target tissue or may be introduced in a LASER BEAM FINAL PROCESSING AND TISSUE TARGETING UNIT. This is usually a biomicroscope or an operating microscope which allows very fine and precise targeting of the tissue while magnifying it. This is normally hand moved by the physician who may use a micromanipulator for a better mechanical resolution of the movement.

In both manual and computer controlled functioning the physician must have the possibility to control the working parameters and should receive information about the working and exposure parameter on the equipment or computer display. The main parameters which have to be fixed (controlled) by the physician are, particularly for LLLT[8] :

- START/STOP of the laser, including the EMERGENCY STOP which is a mandatory function regardless the type of equipment.

- RESET function which allows initializing of all the equipment parameters, particularly the specific irradiation parameters.

- WORKING CONDITIONS which mean the laser beam wavelength, the beam power or energy to be used, the irradiation time (usually for cw operation) or the total number of pulses to be used for exposure; all these parameters should be chosen by the physician either for working under manual control, or by choosing the menu on the computer panel.

During exposure the equipment should display the following information about the currently used parameters to allow to the physician to take the necessary decisions:

- LASER BEAM WAVELENGTH.

- BEAM ENERGY / POWER
.
- PULSE REPETITION RATE, if the laser works in pulsed regime.

- TOTAL NUMBER OF PULSES for current patient exposure. An alternative parameter

to display related to the exposure is the irradiation time per current patient.

- READY-FOR EXPOSURE signal which should be visual (LED) and/or acoustic (buzzer).

- EMERGENCY STOP, which is actually not a displayed parameter but a particular, easy

accessible and operable switch which may be activated in emergency cases by simple push.

4. Doze calculation for laser irradiation
The irradiation doze is defined as the total amount of energy transmitted inside the irradiated tissue; it is measured in energy units, namely J[9]. In practical clinics the doze is also expressed in terms of energy densities (radiant exposure) since this approach describes better the practical needs in expressing the tissue irradiation conditions; more than that it seems that the doze expressed in energy density units is more convenient to use while treating tissue larger surfaces. So, for a cw laser , the doze D is given in this case by:

$$D(J/cm^2) = P(W) \times t(s) / A (cm^2) \qquad (7)$$

where P is the laser beam power transmitted to the irradiated tissue expressed in watt, t is the irradiation time expressed in seconds and A is the area of the treated surface expressed in square centimeters.

The unit J/cm^2 is according to the International System of Units (SI) a derived unit. From eq. (7) it results that if the doze D and cw laser beam power P are known (recommended) the irradiation time may be found after properly choosing the exposed surface area A:

$$t(s) = D(J/cm^2) \times A(cm^2) / P(W) \qquad (8)$$

If the laser works in pulsed regime (as is the case of a significant number of medical diode laser systems) the doze D is given by:

$$D(J/cm^2) = E_p(J) \times f(Hz) \times t(s) / A(cm^2) \qquad (9)$$

where E_p is the average pulse energy expressed in J, f is the pulse repetition rate expressed in Hz, t is the exposure time expressed in seconds and A is the area of the irradiated surface on the tissue expressed in square centimeters. The average pulse energy may be computed by multiplying the peak power per pulse P_p to the pulse time width ? ? and dividing the result with a factor m which depends on the pulse time shape.

$$E_p(J) = P_p(W) \times \Delta\tau(s) / m \qquad (10)$$

For a triangular time shape of the pulse m=2.

The exposure time t while using lasers working in pulsed regimes is then given by:

$$t(s) = D(J/cm^2) \times A(cm^2) / [E_p(J) \times f(Hz)] \qquad (11)$$

Laser and laser products classes related to their use

Criteria for laser and laser products classification
Starting from accurate experimental tests regarding both the damage threshold for
various kinds of tissues at different wavelengths and different exposures, the Maximum Permissible Exposure (MPE) levels have been defined for the eye and the skin.

For the eye, MPE limits have been set both for diffused light originating from an extended source and for intrabeam viewing of collimated radiation, in which case the laser beam may be sharply focused on the retina.

From these MPE levels are derived classification criteria for lasers and laser products, both for pulsed and continuous wave regimes; according to these criteria the lasers and laser products are included in different hazard classes and the related indications on the safety rules are made in order to be followed by all the lasers manufacturers and users. The classes which have been defined as mentioned above have the following hazard characteristics:

For lasers
CLASS 1 laser
The laser in this class is inherently safe. For the lasers included in this class, even under direct intrabeam viewing condition, no injury can be induced by the beam.

CLASS 2 laser
For the lasers included in this class, the direct intrabeam viewing is not dangerous for exposure times shorter than 0.25s, which is the generally accepted time for the eye aversion reaction, including the blink reflex (when exposed to visible laser radiation).

CLASS 3A laser
For the lasers in this class the direct intrabeam observation by optical systems such as binocular telescopes or eyepieces may be hazardous . Direct laser beam observation by naked eye is not dangerous for exposure times shorter than 0.25s.

CLASS 3B laser
Near these lasers, direct intrabeam viewing is always hazardous. Viewing laser light diffused by a screen is not dangerous at distances longer than 13cm and for maximum viewing time of 10s.

CLASS 4 laser
The lasers in this class, when emitting in visible and IR-A are capable of producing hazardous diffuse reflections;

they may cause skin injuries and constitute fire hazards, their use requiring extreme caution.

For laser products
The classification of the laser products is applied independently of the lasers
included in the products because it is derived from the accessible limit (AEL) to an operator. If, for instance, the human access to the laser radiation is completely avoided by the laser product construction itself, a laser product included in CLASS 1 may contain a laser classified as CLASS 4.

Starting from these considerations the laser products classification is the following:

CLASS 1 laser product
Any laser product which does not allow human access to laser radiation in excess of the AEL of CLASS 1 laser.

CLASS 2 laser product
In this class are introduced laser products which allow human access to laser radiation at levels not higher than AEL for CLASS 2 lasers, in the spectral range 400nm - 700nm and do not allow human access to laser radiation at levels higher than AEL for CLASS 1 lasers for any other wavelength.

CLASS 3A and CLASS 3B laser product
In these classes are included any laser products which allow human access to laser radiation at levels higher than AEL for CLASS 1 and CLASS 2 lasers, but do not permit human access to laser radiation at levels higher than AEL for CLASS 3A and CLASS 3B lasers.

CLASS 4 laser product
In this class are introduced the laser products which allow human access to laser radiation in excess of the AEL specific to CLASS 3B lasers.

Requirements for medical laser products
According to the Internationally agreed regulations, each medical laser product has to comply with all the general requirements specific to the laser products of its class, regardless of the application type in which the laser product is used. At the same time, for each medical laser product is recommended that extra parts (pieces or units)/information should be supplied by the manufacturer such as:

- a subunit incorporated in each medical laser equipment for the measurement of that laser radiation level which is intended to be used for irradiation of the human body; this requirement applies specially for CLASS 3B and CLASS 4 medical laser products. The instrument for the above mentioned monitoring should exhibit an overall measurement error of no more than ±20%.

- instructions for each medical laser equipment, specifying the procedure and the schedule for the calibration of the measurement system.
- a target indicating device, for CLASS 3B and CLASS 4 medical laser product.

Practical procedures recommended for the safe use of medical laser equipment

In this chapter are introduced the main elements which should be considered in order to assure the safe use of the laser beams in medical applications.

These elements are analysed taking into account that the laser beam propagates with the speed of light (300,000 km/s) and consequently, once emitted there is usually nothing which could be done to avoid an accident if the initial protection rules were not
strictly obeyed.

Room arrangement and instruments selection

The main steps to take along these two lines are the following:

1. Mounting in front of the door where the laser treatment takes place a pulsed low power bulb fixed inside a standard box with light transparent yellow walls. The controle of the bulb functioning should be made from inside the room at laser operator disposal. On the front wall should be drawn in red the laser safety sign according to the CEI instructions

2. Mounting in the immediate neighborhood of the door a box with a pair of goggles in it answering the laser protection needs specific to the laser used in the room which should be used by the person who enters in the room after requesting permission to enter.

3. Mounting of a plane Laser Danger sign on the door where the laser equipment is mounted and where it is currently used. The sign should be drawn in accordance with CIE specific standards.
4. Inside the operation room where the laser beam is used the walls should be painted in mat colors or should have applied ceramics in dull colors to avoid laser beam accidental reflections.

5. The surgical instruments which are used during the laser irradiation should have optical mat black colors to avoid any accidental reflections of the laser beam inside the operation field.

6. The electrical supply of the laser equipment should be made not on the floor even if the connections are mechanically protected but from upside to avoid accidental hung up by patients or the personnel; present in the operation room.

7. Using of fire proof tubing (such as anesthesia tubing) in the laser beam proximity during operation to avoid fire hazards.

8. Mounting of a system to evacuate the product gases following the laser burning of the tissues, in the immediate proximity of the laser beam impact point on the tissue to avoid spreading of the smoke (which is toxic) in the room.

9. If the laser equipment has a built-in high voltage unit (such as in the case of excimer lasers, nitrogen lasers, pulsed CO_2 lasers, etc) it is recommended to mount in the room a
ventilation system to evacuate the ozone which produced from the atmospheric oxygen due to the high voltage discharges.

10. Mounting the equipment in accordance with the electrical and fire protection regulations.

Laser safety rules for the patients and the personnel

The following rules should be taken into account in the process of the medical use of lasers:

1. Never look in the direct intrabeam viewing direction of the laser beam even if the laser is recently stopped and even if protection goggles are on.

2. Always use protection goggles fitted to the wavelength(s) of the laser beam used for the medical treatment. The goggles should be used by the medical personnel participating in the operation (laser application procedures) and, if necessary by the patient. The goggles should protect from lateral incoming directions of the laser beams with respect to the eyes.

3. Always localize the Emergency Stop button of the laser equipment to be able to activate it easily whenever necessary.

4. Avoid accidental exposure of the skin to the laser radiation even if protection gloves are wored; avoid the exposure of the protections surgical coats to the laser beam.

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