COMPUTER-ASSISTED LASER HAZARD CALCULATIONS AND A CRITICAL ANALYSIS OF THE PREDICTION EQUATIONS

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(A computer program for laser hazard calculations with graphical output over the hazardous range is described. The assumptions implicit in the prediction equations in frequent use are examined and anomalies suggested.)

The application of lasers to both industrial and research purposes is becoming a widespread phenomenon. In this paper we shall deal specifically with the hazard evaluation of lasers emitting in the visible region of the spectrum. Gas lasers emitting at visible wavelengths are the most common and their uses include; surveying, rangefinding, alignment of tunnelling machines, pipelaying and holographic testing. Such lasers produce high intensity monochromatic beams of low divergence (i.e. well collimated) and because of these properties an optical system such as the human eye is capable of focusing a laser beam into a very small volume. The retina of the eye is particularly susceptible to damage from the heating effect of a focused beam. Accidental viewing of either a direct or specularly reflected laser beam may result in the production of thermal lesions on the retina. Such lesions may or may not seriously impair vision depending upon the extent of the lesion and its position within the visual field.

To evaluate the potential hazard of a particular laser one must first predict the power density likely to fall on the retina by direct viewing of the laser beam and it is to this matter that we now turn our attention. A number of authors have given methods for the calculation of retinal beam spot size and intensity 1,2,3,4,5,6,7. In summary, the light intensity incident on the retina is dependent upon the power transmitted through the eye and the size of the laser spot on the retina. The latter two quantities are in turn dependent upon; the transmission of the eye at the particular laser wavelength, the output power (or pulse energy) of the laser, the beam diameter at the output aperture, beam divergence (see Fig.1), pupil diameter, the distance of the observer from the laser, atmospheric attenuation and the degree of accommodation (of focusing) of the eye. For the purposes of hazard evaluation the accommodation of the eye will be taken to be that for which the retinal spot diameter will be a minimum i.e. the worst case condition.

Fig. 2 shows the calculated retinal intensity as a function of distance from a helium-neon gas laser operating at a wavelength of 632.8 nanometres with an output power of 3 milliwatts, an output beam diameter of 1 millimetre and beam divergence of 1.5 milliradians. A pupil diameter of 5 millimetres was used. These calculations are largely derived from the method given by Solon et al [1], however a lower limit of 7 micrometres has been set to the diameter of the beam spot size. This 7 micrometres limit is believed to be that for which the minimum optical abberation can be achieved by the human eye. Atmospheric attenuation has also been taken into account although it is insignificant over the range of Fig. 2.

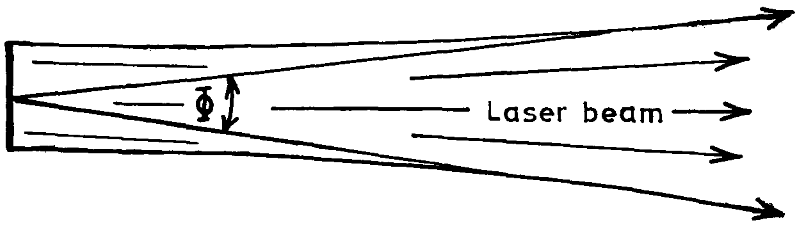

Fig.1. LASER BEAM DIVERGENCE ANGLE Φ

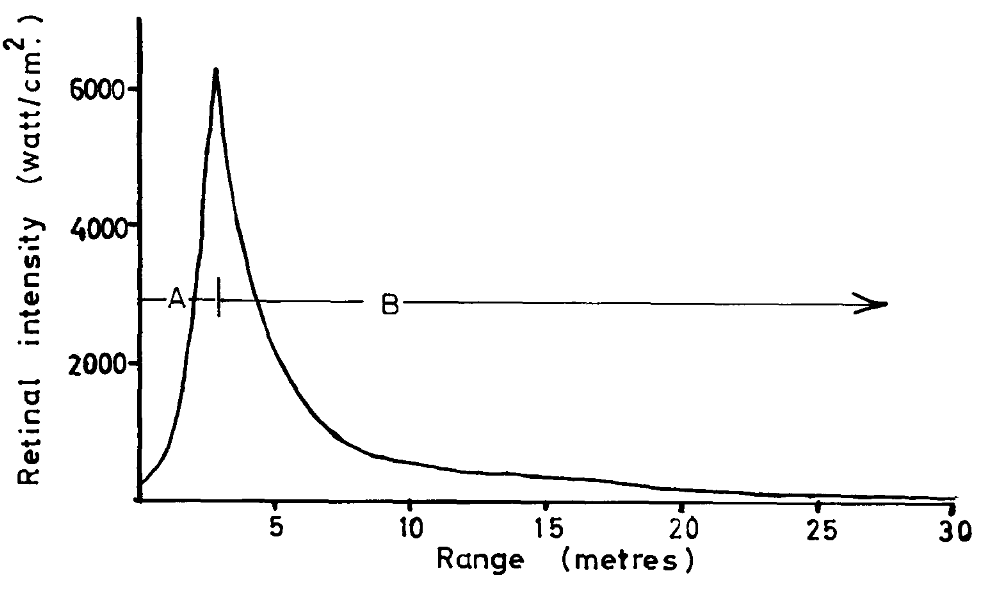

Fig.2. RETINAL INTENSITY VS. DISTANCE FROM LASER

For the sake of analysis three separate cases are considered; two cases close to the laser in what is termed the "near field" and the third case in the "far field" where the laser spot on the retina is no longer resolved and is determined by diffraction at the pupil. In Fig. 2 region A is the near field region and region B is the far field region. The large variation in intensity is due to the fact that the laser beam diverges slightly.

In the far field, although the laser spot on the retina has a constant minimum size the power entering the eye decreases due to beam divergence and falls in proportion to the inverse of the square of the distance (provided the laser beam diameter at the eye is larger than the diameter of the pupil).

The large variation of retinal intensity with distance from the laser close to and within the near field region is a factor which should be taken into account for proper hazard evaluation.

We decided on a graphical approach to hazard evaluation and a computer program was written in Fortran to give graphical output from a normal printer output terminal. Scale factors are selected by the program to give a graph out to, and slightly beyond, the region where the calculated retinal intensity falls below the permitted exposure level. An absolute limit of 2 kilometres has been placed on the graphical range, because at such distances atmospheric shimmer of the laser beam becomes appreciable and intensity predictions will have a large uncertainty factor. The predicted retinal intensity is plotted as a function of distance from a given laser. The "permitted exposure level" for accidental viewing of continuous wave lasers is also plotted. Graphs are plotted for three different pupil diameters corresponding to different ambient lighting conditions. The formula we adopted for the "permitted exposure level" is given by equation 1.

$$I = 1.0/d \quad \text{(see reference 7)} \qquad (1)$$

I = permitted retinal intensity for accidental exposure to continuous wave lasers (watts/cm^2).

d = laser spot diameter on retina (millimetres).

Fig. 3 shows the permitted retinal intensity plotted together with the calculated retinal intensity for 3 different pupil diameters for the same laser as in Fig. 2.

It should be noted that the accuracy of any intensity calculation made is limited by the accuracy of the laser beam divergence which is adopted. We have found that for helium-neon lasers, beam divergence often varies up to 50% of the nominal value stated by the manufacturers. Similar variations can be present in the output power. A graph such as is shown in Fig. 2 is therefore applicable to the particular laser for which the beam parameters have been measured but it does not necessarily apply to other lasers of the same brand and model number.

In many cases the various prediction equations given in literature 1,2,3,4,5,6,7 do not agree with one another in all regions of the laser field, although the shape of the curves obtained is often similar.

Burnett[2] gives an equation for the near field divergence-limited case, which includes a term inversely proportional to distance from the laser, in an expression for the laser image diameter on the retina. When the near-field divergence limited case occurs at small distances from the laser this would make the image diameter calculated from Burnett's equation excessively

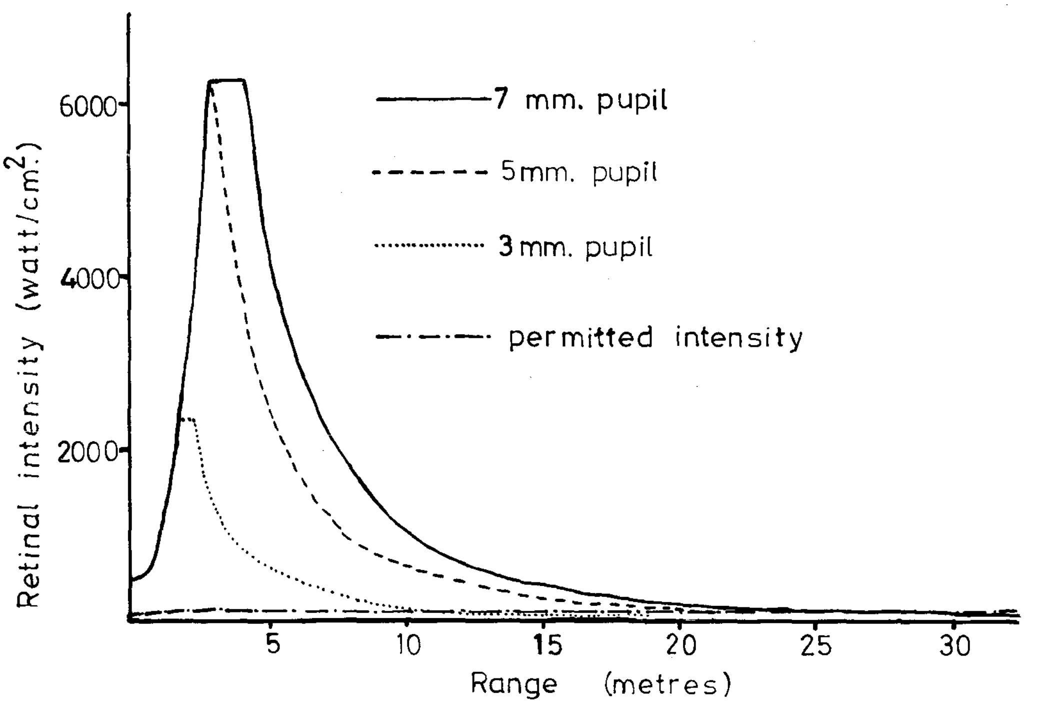

Fig. 3. RETINAL INTENSITIES FOR DIFFERENT PUPIL SIZES

large for realistic hazard analysis. Burnett's equation is correct for calculating the <u>image</u> size of the laser beam aperture on the retina for an accommodated eye, but incorrect as a worst case analysis. The worst case analysis of laser hazards should allow for the minimum possible beam spot size on the retina. In the near field divergence limited case the minimum spot size does not correspond with the image of the laser aperture on the retina, but occurs instead in the focal plane of the lens. Therefore the worst case occurs for an eye focused at infinity and not as Burnett initially assumes for an accommodated eye. In a later publication[3] Burnett gives a simpler equation which is more nearly correct. Burnett[2] gives a beam diameter which is different from that used by Solon et al[1], although the difference is compensated somewhat by the different equations used to calculate retinal intensity. It would appear however that the method given by Solon et al is more accurate for hazard analysis in all cases and we therefore favour their method.

One factor which has not been allowed for in hazard analysis calculations of this type is that of power or energy profile across the beam. All hazard calculation methods given to date assume an even power distribution out to the beam edge. Many lasers have a power distribution which follows a gaussian pattern in the far field (TEM_{00} mode). For these lasers and where the beam diameter is much larger than the diameter of the pupil the worst case retinal intensity may be 50% greater than that calculated when a uniform power distribution is assumed.

The hazard evaluation methods put forward by the various authors are not all in agreement. The investigation of the disagreement is difficult because in some cases assumptions and approximations made have not been fully stated. Furthermore, the use of the formulae given in the literature may lead to errors of hazard analysis where assumptions and approximations are not fully stated or where the method of application of the formulae proposed is inappropriate.

References

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