PHYSICAL AND MATHEMATICAL CONSIDERATIONS ABOUT LASER PERIMETRY *

L. FAVELLA (1), L. LIUZZI (2), F. BARTOLI (2)

(1) Institute of Theoretical Physics and Institute of Informational Sciences, University of Turin, Italy
(2) Eye Clinic, University of Turin, Italy

The physical and mathematical characteristics of white light, monochromatic light, and laser light, are discussed with reference to the advantages offered by perimetry using a red helium-neon laser.

Personal perimetry experiments with different types of light showed that earlier and more distinct evidence of loss could be obtained with a laser source (Liuzzi and Bartoli 1972*a*, 1972*b*, 1973). The laser employed was of the helium-neon type and had the following characteristics: wavelength 6328 Å ; band width 0.1 Å ; power 0.5 mW ; beam diameter 0.8 mm.

As can be seen from the wavelength, a monochromatic red light was obtained. There are two advantages in using a laser of this kind. In the first place, retinal sensitivity is lowest in this region and the eye is therefore examined under stress; in the second place, beam energy is easier to control, since the energy of red photons is the lowest in the visible spectrum.

An explanation of the better results obtained with laser as opposed to white light, monochromatic light in general, and monochromatic light obtained with the aid of interference filters, is given in the present paper.

A word or two may first be said concerning the main differences between lasers and non-laser light. Two features of particular importance: the much greater monochromaticity of laser light (beam bandwidth of 0.1 Å in our case, as opposed to more than 150 Å given by interference filters), and its coherence.

The following expression can be used to represent a monochromatic laser beam in air:

$$F(x, t, \nu) = A \sin 2\pi\nu \left(t - \frac{x}{c} - \varphi(\nu)\right)$$

where:

ν = frequency
λ = wavelength
c = speed of light in vacuo
t = time
A = amplitude

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x = distance of the point under consideration on the x axis from its origin
φ = phase

The phase parameter is used to express early or late arrival of the wave maximum with respect to the point in the cross section where the maximum is present at the given time t. When $\varphi(\nu)$ is positive, there is a delay with respect to the point where $\varphi = 0$ at time t ; when φ is negative, it represents an advance.

In ordinary non-laser light, $\varphi(\nu)$ is a random variable for different points of the cross section of the beam. With the laser, on the other hand, $\varphi(\nu)$ is constant over the entire beam, apart from slight variations on the edges. It is for this reason that laser light is said to be coherent.

Coherence gives rise to speckles, caused by interference. When a laser beam is projected on to a diffuse reflecting surface at right angles to its direction, for instance, the spot of light will be seen to have a shimmering, granular appearance. This is not caused by air turbulence or thermal instability within the beam, but to the spatial coherence of laser light, i.e., the fact that $A(\nu)$ and $\varphi(\nu)$ are virtually constant over a finite region of the beam. The reflected beam usually consists of a large specular component, coupled with other components due to random irregularities on the diffusing surface.

On the focal plane of an observing optical system, such as the eye, these components are seen as randomly distributed interference spots. Saccadic and, to a lesser extent, all other eye or head movements, will be accompanied by a rapid change in spot pattern, so that a granular structure is apparently conferred on the laser spot.

The statistics of laser light is also important. A light beam is a flow of photons in a fixed direction and its intensity in an infinitesimal cross section (δS) is given by the number of photons crossing such section per second, i.e., the photon flux. When times of the order of 10^{-6} to 10^{-9} sec are considered, this flux is not constant, though the beam is nevertheless treated as having a macroscopically constant intensity. Fluctuations occur and are dependent on both the time interval chosen and the light source.

Let us consider a parallel beam of monochromatic photons, with a well-defined cross section, from both an ordinary incoherent and a laser source, and let us count the number of photons crossing a normal beam section in a small time interval τ (e.g., $\simeq 10^{-5}$ sec), i.e., n_τ. Fluctuation will mean that this parameter is a random variable, whose probability distribution $P_t(n)$ indicates the probability that exactly n photons will cross the beam during time t. Experiments have shown (F.T.A.) that coherent laser and noncoherent light with the same wavelength have different distributions, namely:
a Poisson distribution (coherent light):

$$P_\tau^{(L)}(K) = e^{-\lambda_{L\tau}} \frac{(\lambda_{L\tau})^K}{K!}$$

where $\lambda_{L\tau}$ is the mean n_t value for laser light and is proportional to the intensity;
and a Bose distribution (incoherent light):

$$P_\tau^{(INC)}(K) = \frac{1}{1+\lambda_{I\tau}} \left(\frac{\lambda_{I\tau}}{I+\lambda_{I\tau}} \right)^K$$

where the tail decreases much more slowly as K increases.

This difference is still apparent when τ is replaced by $T = m \cdot \tau$, while the average value of n_τ is kept constant. Laser light still has a Poisson distribution and incoherent light has a Pascal distribution; once again, the second tail decreases more slowly.

In our experiments, laser perimetry gave the best results, followed by red light from interference filters and white light (in that order). This is clearly attributable to differences in response on the part of the diseased region of the retina. In the case of healthy areas, of course, the different stimuli are normalised to give the same subjective response probability.

Two phenomena, both dependent on the characteristics of the light involved, are responsible for this differences in response. The first is a consequence of the statistics. The second is due to the effect that the laser structure has on the inhibition mechanisms of retinal horizontal and amacrine cells. In the latter connection, it will be recalled that a speckling effect is produced on the retina by laser light diffused by the spot on the screen. The resulting inhibition is similar to that produced by a windmill spinning light; in physiological experiments, this caused an increase in the response threshold.

As far as the statistics is concerned, reference may be made to results given by a very simple mathematical model wherein the eye is considered as a number of photoreceptors connected to a « black box » (similar to von Neumann and McCulloch's mathematical neuron) that responds only when excitation is greater than a fixed threshold.

Two types of photoreceptor, requiring $\geq \alpha$ and $\geq \beta$ ($\beta > \alpha$) photons, respectively, to elicit a response, are postulated. Those of the second type are pathological and it can be shown that their response probability is critically dependent on the tail of the distribution of the intensity. If red laser and red incoherent light is adjusted to give the same subjective response probability at a healthy point, in fact, the probability will differ considerably when an area with diseased photoreceptors is hit. This is due to its higher threshold and to the fact that such adjustment means that the residual tail for intensities greater than β will be longer for incoherent than for laser light.

The same is true when white and red incoherent light are compared, with the latter taking the part of the laser since its distribution has a shorter tail than white light. This fully agrees with our finding of a lower response probability for red interference as opposed to white light.

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Dr. Franco Bartoli, Clinica Oculistica dell'Università, Via Juvara 19, Torino, Italy