LASER OPHTHALMOSCOPE AND COHERENT LIGHT*

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SINCE the advent of laser sources producing coherent light, that is plane polarized and emitted as an almost parallel beam, there has been much conjecture about its use in ophthalmological practice. The human eye, with its clear media capable of refracting a parallel beam to image on the retina, appeared to be the logical target for such a unique source. The tissue reaction consequent to the retinal image of a laser source made it certain that its place as a phototherapeutic source would be investigated in relation to choroido-retinal pathology.

Our original aim was to produce a convenient ophthalmoscopic laser device which would be more convenient to manipulate than the existing xenon lamp source (Ingram, 1964). Other features which encouraged the development of such an instrument were the ability to undertake treatment without the use of topical or retrobulbar anaesthesia and the resultant definitive choroido-retinal lesions reducing the area of damage and the risk of secondary sequelae such as vitreous involvement with vitreous traction band formation. Not least among our considerations was the desire to make a moderately-priced instrument widely available, so avoiding the invidious practice of having to refer patients to a few centres fortunate enough to possess a light coagulator.

Instrument Design

In designing a ruby laser ophthalmoscope, several factors have to be taken into consideration. Not only must we have a device for applying a laser pulse through the pupillary aperture of an eye, with an auxiliary illuminating viewing system, but we must be able to produce a laser emission with a total energy and beam divergence which are such as to give retinal energy densities of approximately 0.4 to 0.8 joules per sq. cm. It must be borne in mind that the mode pattern, beam diameter, and beam divergence may vary a great deal between one laser and another; for example, in the present instrument we have an energy of 0.29 joules from a laser having a beam divergence of approximately 0.5° which is then passed through a $\times 2.5$ reducing telescope resulting in a beam divergence of 1.25° which, in a perfect eye (calculating the diffraction limited image size), gives a retinal energy density of 3.4 joules per sq. mm. In practice, however, with the imperfections of the optical system of the eye, the retinal energy density is about 0.8 joules per sq. mm. This falls into the

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range where stimulation of collagen synthesis (Lawrence, 1967) occurs, whereas the energy density of 5.0 joules per sq. mm. falls in the range where collagen synthesis is inhibited. Apart from the choice of the therapeutic range of retinal energy densities, the protection of the observer's eye is a most important consideration. The ophthalmoscope which we have developed employs separate optical systems for the laser and for viewing, thus reducing the risk from specular reflections. A more positive protection against reflection from the corneal and lenticular surfaces is achieved by means of a permanently incorporated Schott BG 18 filter, providing a large safety factor in relation to the ophthalmoscope emission at 6943 Å. Some parameters in radiation safety in relation to protection devices have been reported by Straub (1965), and others are covered by the proceedings of the First Conference on Laser Safety (1966).

We have demonstrated by directly irradiating a rabbit's eye with a maximally-dilated pupil that it is possible to produce a thermal burn of the retina from a 2" xenon flash tube similar to that incorporated in the ophthalmoscope (Fig. 1). The energy level obtained in this experiment was approximately 1.6 joules per sq. mm. at the retina and this is comparable to the temperature necessary for protein destruction (Voss, 1962). When using the ophthalmoscope with its flash tube *in situ* but with an unmirrored ruby rod to prevent laser emission, it has been demonstrated that there is no danger whatsoever of producing a thermal burn of the retina. The amount of xenon flash tube light emerging from the laser optical train of the ophthalmoscope can produce an energy density at the retina of only a fraction of a millijoule per sq. mm. Without being more specific about detail and design, it is probable that the ideal arrangement would be a coaxial laser and illuminating system allowing synchronous focusing of the laser image and target graticule on the retina in all degrees of ametropia. The possible optical arrangements are, however, legion and are limited only by the ingenuity of the designer.

Irrespective of the final place of laser sources in retinal phototherapy, it is surprising that as yet a compact hand-held "cold light source" for ophthalmic phototherapy has not been achieved.

Clinical Applications

It has been repeatedly demonstrated histologically that laser applications produce adhesion of all the retinal layers to the choroid. The extent of the separation of the retinal layers from the pigment epithelium may be limited by using a suitable laser source, as indeed it may be with other types of phototherapy. Immediately after application, swelling and tissue separation of all the retinal layers occur, associated with partial or complete disruption of the pigment epithelium. The initial central bubble disappears within a few minutes to be replaced by the clinical appearance of "retinal oedema". The peripheral halo of pigment which surrounds the lesion is due partly to the force of the disruption and partly to the central pigment clumps' being obscured by the oedema. A full-thickness reparative reaction develops from 7 days with a normally-pigmented fundus. The involvement of the choroid in the subsequent lesion is fortuitous but not necessary in preventing intraretinal separation. Unlike the more extensive changes resulting from the thermal lesion of an arc source, it may well be that not all the cells are destroyed at the site of the lesion and repair occurs within the site of the irradiated area. Collagen synthesis as a result of laser irradiation may be stimulated as seen in skin (Lawrence, 1967), and this may be indicative of an active reparative process.

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FIG. 1.—Flash burns produced by a $2'' \times \frac{1}{4}''$ xenon arc source working at 1 mega watt. The collimating system was employed, allowing 0.2 J. to enter the rabbit's eye as a nearly parallel beam with an application time of 1 msec. The image of the trigger mechanism for the xenon arc source can be seen clearly on the retina.

FIG. 2.—A temporal detachment of the retina associated with a retinal dialysis effectively limited by multiple laser applications.

FIG. 3.—Immediate laser lesions with central bubbles in relation to a choroidal rupture—Case 1.

FIG. 4.—Retinal haemorrhage indicative of laser overdosage.

It has been suggested by Zaret (1965) that selection of cases suitable for phototherapy is limited by the existence of apposition of all the retinal layers to the underlying choroid. In considering the nature of retinal separation in selected cases for phototherapy, he stated "The pigment epithelium has not detached and is firmly adherent to the adjacent choroid external to the principal portion of the retina, which has become displaced internally. For photocoagulation in this instance, laser radiation would be far less effective than the Meyer-Schwickerath apparatus, as the latter readily produces coagulation throughout all the layers of the retina".

The success of a technique, whether thermal coagulation or otherwise, obviously requires the apposition of the retinal layers to the pigment epithelium and underlying choroid. Where such apposition does not exist the aim of retinal surgery is to produce it by drainage or absorption of the interface fluid to allow a permanent chorio-retinal band to form subsequently. We are unaware of the circumstances which allow xenon phototherapy or laser phototherapy to bridge an actual intraretinal separation.

The present Keeler-I.R.D. instrument based on our original prototype has done much to meet the desirable criteria for retinal phototherapy and at the same time it has proved a safe instrument in terms of the operator's eye. Many hundreds of applications have been made by individual operators without any personal ocular sequelae over a period of 3 years, initially using prototypes and latterly the commercial instrument. The instrument has proved capable of treating most eyes in which a good view of the fundus can be obtained. The cases in which failure to mark the retina has occurred have included some high myopes with albinoid fundi, and eyes in which an adequate pupillary mydriasis was unobtainable, or in which opacities of the media scattered the laser light. We have repeatedly checked the efficacy of laser retinal applications against coagulations with a xenon source and have reached the following conclusions:

- (a) Failure to cause a retinal lesion with the laser ophthalmoscope almost certainly implies that a xenon source will also prove ineffective.
- (b) The histological lesions resulting from an adequate laser application involve all the retinal layers in adhesion to the choroid and are not limited to the pigment epithelium and choroid.
- (c) Providing pupillary mydriasis is maintained, there is no limit to the number and extent of applications which may be produced at one time. Incomplete passage of the laser beam through the pupillary aperture resulting in "iris cut-off" produces an irregular miosis and mydriasis must again be obtained before effective treatment can be applied.
- (d) The mature adhesion is capable of preventing further progress of a detachment if the applications are suitably deployed (Fig. 5a-d, overleaf).
- (e) Massive haemorrhage will not result from inadvertent involvement of retinal vessels as these are unaffected (by virtue of the nature of the ruby laser emission at 6,943 Å). Abnormal retinal vasculature sometimes appears to be affected by a ruby laser emission.
- (f) Focal haemorrhages through moderate laser overdosage are absorbed quickly without sequelae even in ambulant patients. They are, however, a sign of overdosage and either a lower energy setting should be selected or the retinal energy density should be reduced by defocusing (Fig. 4).

- (g) The clear media remain clear in the dosage regime obtainable from this instrument and we have not seen sequelae due to vitreous changes. The power must be increased by a large factor to affect the clear media (Q-switching to produce 20 mJ. in 20 nanoseconds (approx. 1 MW) is required to produce changes in the clear media from a single pulsed emission).

FIG. 5.—Diagrammatic distribution of laser applications.

Dangers of Laser Phototherapy

The possible danger of producing brain damage and other effects when treating an eye with the laser has been raised by more than one author, though as far as we are aware they have produced no experimental proof of such damage applicable to the dosage range of our instrument used on human tissues (Zaret, 1965; Mellerio, 1966; Marshall and Mellerio, 1967).

Our evidence strongly suggests that it is impossible to damage the human central nervous tissue by applying to a human globe the order of dose emitted by this laser ophthalmoscope. A greater energy than anything which is, in fact, available in an ophthalmoscope is required to produce such damage, even in experimental animals with a very thin cranium (Earle, Carpenter, Roessmann, Ross, Hayes, and Zeitler, 1965). We have, for other reasons, treated the orbital region of patients with retinal dosages of 3,500 joules per sq. cm., *i.e.* up to forty times the retinal energy density employed with the laser ophthalmoscope, and clinically no neurological changes have resulted. The existence of shock waves which might be thought capable of producing brain damage has been demonstrated (Mellerio, 1966). However, to generate these ultrasonic waves with sufficient amplitude to produce actual damage, laser outputs far in excess of that which the ophthalmoscope is capable of producing are required.

Clinical Data

To provide an indication of the type of treatment one may undertake with a laser ophthalmoscope we have analysed the first 63 treated cases with over a year's follow-up. These fall into the following categories:

- (a) Laser treatment of an acute detachment in association with other surgical methods—10.
- (b) Sealing a retinal hole either without a co-existing detachment or when the detachment is limited to the immediate area of the hole—10.
- (c) Laser treatment used alone as a primary procedure to treat an acute detachment—4.
- (d) Prophylactic treatment to an eye where the contralateral eye has experienced a detachment—11.
- (e) Laser treatment to a progressive detachment when the contralateral eye has been involved in a detachment—1.
- (f) Prophylactic laser treatment to prevent progression of a detachment treated by other surgical methods—4.
- (g) Laser treatment of retinal pathology where no detachment exists—12.
- (h) Laser treatment to limit the extent of a progressive cystic detachment—4.
- (i) Laser treatment to a progressive cystic detachment where the first eye had been involved in a detachment consequent to a retinoschisis—1.
- (j) The treatment of macular holes or cysts—3.
- (k) The treatment of disinsertions by laser therapy alone—3 (Fig. 2).

In four of the above cases discrete haemorrhages were a feature of the laser applications, but they absorbed within a few days and left no trace or damage.

In group (a) one case, in which multiple surgical detachment procedures including retinocryopexy and light coagulation had been undertaken, was a failure from the outset.

The remaining cases in the various groups have remained satisfactory. Five cases are described in detail to illustrate the type of case in which we have employed laser phototherapy; Cases 1, 3, and 4 have been excluded from the figures previously quoted because of their limited follow-up period.

Case 1, a woman aged 33 years, had a choroidal rupture at the posterior pole as a result of a blow from a crowbar. Initially there was macular oedema, the visual acuity being perception of light only. The rupture was outlined with laser applications producing immediate lesions with small central bubbles but no haemorrhages. Pigmentation developed slowly but was obvious on the eighth post-application day. The vision improved to 6/18 unaided and the retina remains flat (Fig. 3).

Dosage: Input setting—560 J
Output energy—0.34 J
Retinal energy density 0.92 J./sq. mm.
Applications not defocused.

Case 2, a man aged 30 years, had attended for 10 years with a right proliferative retinal vasculitis and a secondary cataract. The left fundus showed a periphlebitis with some proliferative changes in relation to the superior temporal vessels and there was a disinsertion in the infratemporal quadrant. A simple progressive detachment developed in relation to the disinsertion. Laser phototherapy was applied to the flat retina posterior to the detachment to loculate the infero-temporal quadrant. Fluid resorption occurred and the detachment has not progressed during a 15-month follow-up.

Dosage: Input setting—560 J
Output energy—0.34 J
Retinal energy density—0.92 J./sq. mm.
Applications not defocused.

Case 3, a woman aged 54 years with hypertension, complained of blurred vision in the left eye. Examination showed an occlusion of the left superior temporal artery. In the right eye there was a retinal hole with a raised operculum in the right superior temporal quadrant, but apart from the lips of the hole being raised, the retina was flat. Two concentric rows of laser applications were directed to circumscribe the hole. The outer row was applied at a higher energy level than the inner and was defocused to produce larger lesions. Immediately after application both the focused and defocused lesions showed central bubbles but no haemorrhages, pigmentation developing in 5 days. After 6 months the corrected visual acuity was 6/6 in the right eye and 6/36 in the left. The right retinal hole was involved in a well-localized pigment reaction and the retina remained flat.

Dosage: Input setting—400 J
Output energy—0.14 J
—0.23 J defocused
Retinal energy density—0.38 J./sq. mm.

Case 4, a woman aged 54 years, developed a right superior nasal detachment with a large retinal hole at the equator in the 2 o'clock meridian. A minimal diathermy and drainage procedure initially reduced the detachment which subsequently recurred. Next a radial infold was placed from 12 to 18 mm. from the limbus. The retina flattened but the hole was positioned across the inferior margin of the infold. At this stage the patient was referred to us for phototherapy. Laser applications were applied adjacent to the lips of the hole. Although retinal reaction was observed, it appeared clinically inadequate. Pupillary miosis due to "iris cut-off" prevented further treatment, but 4 days later with good mydriasis following a sub-conjunctival injection of mydracaine further laser applications were made at a higher energy level with satisfactory markings. At 9 days after the first laser applications the choroido-retinal reaction, as judged by pigmentation, was good; some gaps in the line of treatment remained and these were subsequently treated at two out-patient attendances, and the retina has remained flat for 9 months.

Dosage: Input settings—Initial applications 480 and 560 J
Subsequent applications 700 J
Output energy—Initial 0.15 J
Subsequent 0.19 J
Retinal energy density—Initial 0.41 J./sq. mm.
Subsequent 0.51 J./sq. mm.
Lesions not defocused.

The difficulty in producing laser lesions initially in this case was certainly due to the presence of subretinal fluid which was not clinically apparent. In this context the laser may be used to seek out the limits of choroido-retinal separation and apposition.

Case 5, a man aged 36 years, had a right amaurotic eye as a result of an old detachment of the retina which had not been reduced by multiple surgical procedures. He was a high myope and examination showed him to have a retinal hole without a detachment in the 1 o'clock meridian of the left fundus. Laser applications were placed with a linear distribution posterior to the hole, but in this case the hole was not outlined by applications nor was the line of applications extended to the periphery. 18 months later he developed a complete detachment which was not reduced by surgical treatment. Pigment indicating the site of the retinal laser lesions was visible in the detached retinal layers. We concluded from this case that the distribution of the laser applications was inadequate. Whether more extensive choroido-retinal adhesions or a scleral shortening procedure would have limited the ensuing detachment in a long-axis eye with a proclivity to retinal detachment is a matter for conjecture.

Dosage: Input setting—480 J
Output energy—0.24 J
Retinal energy density—0.65 J./sq. mm.

Mechanisms of Laser Lesions

The mechanism of the production of laser lesions must be taken into account in interpreting the results of laser radiation on living tissue. We must consider the possible physical processes which can occur, as it is only by understanding the fundamental nature of these processes that the results can be interpreted correctly and applied to extend the use of lasers in ophthalmology. The first hypothesis which might be considered is that laser energy is absorbed by the tissue and degraded into heat. The nature of the lesion will then be purely thermal. This hypothesis soon becomes untenable as one can show that the same amount of laser energy will not always do the same amount of damage when the method of application is altered. For example, the laser emission may be modified by the use of various means, mechanical, optical (rotating prism), or chemical (photosensitive) substances such as cryptocyanine solution in a cell at the emitting end of a laser rod. Such devices enable the laser emission to be delivered in 2×10^{-8} of a second instead of 1×10^{-3} of a second and, therefore, result in a large increase in energy per unit time or power. When the same energy is employed with the laser Z-switched for instance, 0.1 J. from the non Q-switched ruby laser will produce a discrete lesion in the retina and choroid. When the same energy is employed with the laser Q-switched, however, a punched-out hole is produced in the retina, choroid, and sclera with damage to the clear media of the eye as well. In both these cases the time of application is so short that thermal leakage from the focal zone is insignificant. In addition, experiments with gas lasers emitting 0.025 watts continuously show that a retinal lesion can be produced with temperature rises of as little as 7.8°C. (Kohtiao, Resnick, Newton, and Schwell, 1966) which is clearly insufficient to produce damage in a second or so. In our own experiments it has been possible to produce retinal lesions using a helium-neon gas laser producing as little as 0.005 watts. This lower figure is probably due to the fact that our laser was being run in a diffraction-limited condition.

One may then consider the effects of shock waves to be responsible for the lesions as it can be shown that the material in the focal zone of the laser beam will experience the effect of mechanical forces. These have been measured in various biological systems (Mendelson and Ackerman, 1965) but the authors conclude that they are not of sufficient magnitude to produce significant changes in tissue. We could also try to interpret the effects of lasers by considering photo-ionization or the production of photo-electrons in the tissue, but the cross-sections for these processes do not appear to be high enough to explain the phenomena which we observe. Briefly, however, we must discount thermal or mechanical theories

(Kohtiao and others, 1966; Mendelson and others, 1965). Further, the ordinary effects of a high photon flux do not appear to be capable of explaining the observed effects of laser light. Particularly intriguing is the effect of laser light on melanomata which we (Manson, Smart, and Ingram, in preparation) and others (Goldman, 1966; McGuff, 1966) have observed. Lasers appear to induce changes leading to the regression of the tumour in about 3 weeks which no amount of thermal or mechanical stimulation would be capable of doing, and which has not been observed following irradiation with incoherent light. We have concluded that we must interpret the biological effects of lasers in terms of the scattering of photons by the charge clouds surrounding various larger molecular species in the cells and we must also take into account the probability that the coherence of the light beam will induce resonance phenomena. A mathematical analysis of this hypothesis is being undertaken and the results will be presented by us later.

Conclusion

In applying laser phototherapy to any case it must be remembered that, as with other methods of producing retinal re-attachment, satisfactory adhesion will result only if the choroid and pigment epithelium are in apposition with the other retinal layers. Such contact must exist before successful phototherapy from any source whatever can be achieved. Providing the limitations and correct indications for laser phototherapy are appreciated, we consider it to be of value in routine clinical procedures. This applies particularly to the prophylaxis of retinal detachments where there exists a recognized incidence of bilaterality.

Summary

We have tried to indicate some of the features of a laser ophthalmoscope design in relation to retinal dosage, and clinical application. The types of cases treated have been listed from a series with a moderate follow-up period in excess of one year, and some detailed clinical cases have been included to illustrate these. The mechanisms underlying the production of a lesion in ocular tissue have also been considered as far as our present knowledge allows.

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