Photocoagulation delivery systems for continuous-wave lasers

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The recent discovery of the argon and krypton-ion continuous-wave (c-w) lasers has provided the scientific community with laser emission lines in every portion of the visible spectrum. It is now possible to select laser wavelengths that are highly absorbed by haemoglobin, by the pigment epithelium, by the nuclear retinal layers, or by any ocular structure. Coagulation of these particular layers can be produced by correlating the absorption potential of the target tissue with the proper laser output. By irradiating this tissue with laser light of a wavelength similar to the absorption peak of the tissue, the minimal amount of energy is required to produce a therapeutic effect.

The argon laser (4579Å–5145Å) produces radiation at 8 to 10 wavelengths in the blue-green spectral region; two wavelengths (4880Å and 5145Å) comprising relatively powerful emissions. The krypton laser generates monochromatic light at 6471Å (red), 5682Å (yellow), 5308Å (yellow-green), and 4765Å (blue). By utilizing the proper noble gas and cavity mirrors in the laser system, any of the transitions can be used to create a specific photocoagulation response. Histopathological examinations of irradiated animals has shown that the longer wavelengths of the visible spectrum are transmitted through the retina and are absorbed almost entirely by the pigment epithelium and choroid, while the intermediate and shorter wavelengths of the visible spectrum are absorbed by the pigment epithelium, the outer segments of the rods and cones, and the nuclear layers. The predictability of the tissue response, the precise focusing capability, and the high photon energy of the c-w laser beams are features that will insure a prominent position for these devices in the ophthalmic photocoagulation armamentarium.

The advantageous features of c-w lasers in photocoagulation could not be utilized heretofore, because delivery systems capable of directing the precise beam to the eye were nonexistent. During the past year, four delivery systems involving different optical principles have been constructed for intraocular, anterior segment, and surface photocoagulation. Three of these instruments were designed, modified, or constructed partially or completely at the Bell Telephone Laboratories, Murray Hill, New Jersey. These c-w laser ophthalmic delivery systems are described in subsequent sections with emphasis on technical detail. The clinical photocoagulation techniques and results will be the subject of later reports.

(A) Intraocular argon laser photocoagulation delivery system

An extremely intricate and precise optical relay system was constructed in collaboration with the American Optical Special Products Division in Buffalo, New York. The existing target, focusing, and illumination optics of the American Optical ruby laser photocoagula-

tor were retained (Koester and others, 1969), but the remainder of the delivery system apparatus was redesigned to be used specifically with the c-w argon laser. The components of the intraocular argon laser photocoagulator—the gimballed table mount, the extension tube, the support stand, and the optical head—are illustrated in Fig. 1.

FIG. 1 Intraocular argon laser photocoagulation delivery system, showing laser, gimballed table mount, extension tube, support stand, and optical head

Initially, a gimballed mount intercepts the laser beam and redirects it horizontally, at 90° , through two rotating highly reflective dichroic mirrors mounted in ball-bearing sockets. The entire mount swings around pivot points aligned along the axis of the laser beam. Therefore, the reflected beam can be directed along any position in the X and Y axes at right angles to the original beam. A 1.5 : 1.0 expanding Galilean telescope has been inserted into the first stage of the gimballed mount. Two pressure bolts can be turned to move the telescope slightly, thereby creating a small motion of the expanded laser beam in the same direction. This addition aids immeasurably in aligning the beam when necessary.

A concentric telescoping steel tube encloses the beam from the gimballed table mount to the optical head. This 4-ft tube can be reduced in length by 16 in. and therefore has an 8 in. inwards and outwards movement from its midposition. Motion of the optical head is permitted along the Z axis with this interconnecting gimbal-to-optical head tube, as well as along the X and Y axes previously mentioned. The tube links the motion of the gimballed mount to the laser optical head so that no realignment of the beam is necessary. The laboratory personnel are also protected by enclosure of the beam in the extension tube.

The optical head is supported by a spring-balanced stand mounted on casters. The entire weight of the optical head and extension tube is counter-balanced accurately so that the head may be moved through its full 12-in. vertical excursion by slight pressure. A Y-shaped arm extends from the movable stand and supports the optical head. This arm has a roller-bearing cradle upon which the head can be moved toward or away from the gimballed mount, providing 2 in. of movement in that direction. The arm (and head) can be rotated about the axis of the support stand, permitting 10 in. of horizontal movement. In addition to these excursions necessary for fine adjustment, the entire optical head, support stand, and extension-coupling tube can be moved grossly around the stationary gimballed mount through an arc of 40° horizontally (30 in.) and 20° vertically (15 in.). The support stand also houses all electrical equipment, including rheostats for the aiming and viewing lights.

The most intriguing portion of the entire intraocular delivery system project was the construction of an optical relay head that would retain the highly advantageous properties of the argon laser beam, yet provide the various optical elements that would make argon laser irradiation a safe and sophisticated method of photocoagulation. The following components were considered essential for the optical head of an intraocular argon laser photocoagulation delivery system (Fig. 2).

FIG. 2 Schematic representation of optical components and beam paths in Fig. 1

- (1) A target system—to allow the surgeon to locate the exact intended argon laser impact area before firing.
- (2) Background retinal illumination—to show the tissues surrounding the impact target area for orientation and evaluation.
- (3) Argon beam focusing potential—to permit the minimal amount of energy necessary for retinal coagulation to be transmitted through the ocular media.

- (4) Viewing system—that would have mobility and versatility, provide a large field of view, and neutralize the patient's refractive error.
- (5) Special laser optics—incorporating dichroic mirrors, diffusing elements, and various safety devices particularly effective with argon laser systems (Fig. 3).

FIG. 3 Special laser optical devices utilized during photocoagulation procedures: power meter, beam splitter and attenuation filters near gimballed mount, and extension tube

(1) Target system

The ability to determine the exact location of the intended coagulation spot before transmitting the laser beam through the eye is the most important feature of any photocoagulation system. A separate target system was used that directed the target beam coaxially along the same optical path as the laser. Any maladjustment of the focusing lenses, obstructions to passage of the laser beam such as the iris border, or impediments along the path of the beam (vitreous debris, pigment accumulations) can be detected before the actual delivery of the light energy. An attenuated argon laser beam was considered, at first, as a possible target indicator, but this proposal was discarded because of the poor beam contrast with the fundus and the inherent laser pulsing difficulties that would be encountered. A separate, coaxial, focusable aiming system that directed a bright, sharply demarcated spot on the area to be photocoagulated was chosen.

The ability to select various coagulation sizes is of considerable clinical significance. Large-sized coagulations are advantageous when a large area is to be treated, when delimiting certain peripheral degenerations or retinal breaks, or when a large vascular lesion or arborization of vessels is to be irradiated. Small coagulations are preferable for posterior retinal work to preserve functional visual area, near the macula or optic disc, and for isolated vascular abnormalities. Furthermore, less energy per cm^2 of irradiated retinal tissues is necessary for large coagulations than for small ones, and the total amount of radiation

ultimately entering the eye may be an important factor in some cases. Treating these particular patients with larger-sized coagulations may be beneficial in order to minimize the total energy transmitted through the ocular media.

The aiming spot size projected from the argon laser optical head onto the retina was designed to correspond to the impact diameter of the laser beam. The size of the aiming circle on the retina can be varied to indicate diameters of 1° , 2.5° , and 5° . The aiming beam and laser beam pass through a common field stop so that a change in the field stop size in order to change burn size will change both the aiming spot and laser beam size correspondingly. The common field stop also functions to ensure that the laser beam is coupled optically to the aiming spot, and that both beams will be focused exactly at the same ocular plane.

(2) Background retinal illumination

An illuminated circular viewing area, measuring about 20° in diameter, surrounds the aiming spot. This illumination is obtained by imaging the filament of the tungsten lamp on the patient's pupil like the illumination beam in indirect ophthalmoscopy. The intensities of the aiming and viewing beams are variable, and are controlled by separate rheostats. Usually the weakest background illumination intensity is used consistent with the clarity of the ocular media, in order to provide a highly contrasted aiming spot.

Dichroic mirror M_2 is designed to reflect approximately 60 per cent. of the white light from the tungsten lamp except for the region of the transmitted argon wavelengths. Dichroic mirror M_3 reflects between 40 and 60 per cent. of the white light impinging upon it, depending on the angle of incidence of the light, so that about one-quarter of the light produced by the lamp actually reaches the patient's eye. The surgeon sees only 40–60 per cent. of the light emerging from the eye, minus the argon band, and therefore can appreciate only one-sixteenth to one-eighth of the original available light. Nevertheless, the background retinal illumination is excellent and entirely adequate for photocoagulation purposes.

(3) Focusing potential

The patient's refractive error must be optically corrected in order to produce small coagulations of proper intensity. The size of the treated spot cannot be accurately predicted without neutralization of the refractive error. For the highly ametropic eye, it might be extremely difficult to create a retinal coagulation without reverting to higher energy transmission across the ocular media. In addition, treatments in the periphery or coagulations on highly elevated tumours or intravitreal vessels would be very difficult unless the beam could be focused.

The design utilized in the optical head of the argon laser provides a substantial correction range without excessive motion of lenses. An afocal telescopic system with a magnification of 3 gives a correction range of -12 to $+18$ dioptres with a motion of 24 mm. The system has the property of constant magnification regardless of object distance. Therefore, the size of the target spot, the angular size of the beam into the patient's eye, and the position of the eye will not change with adjustments of the lenses.

An intense aiming spot of white light passes through the same optical mechanism as the laser beam, and when focused on the patient's fundus, will indicate the exact size and coagulation position of the laser beam. In this manner, the laser beam can be brought to a precise focus on any visible portion of the ocular structures by the preliminary adjustment

of the target spot. By moving the afocal telescopic lens system, a clear, sharply-defined circular spot can be obtained. Intravitreal blood vessels, iris abnormalities, and lid lesions as well as chorioretinal defects can be treated with the minimum amount of energy necessary for coagulation. This facet of the system becomes extremely important when periods longer than one second per pulse are required for adequate treatment.

(4) Viewing system

An erecting, focusable, one-third power telescope with 20° field of view and $5\times$ effective magnification in viewing the fundus of an emmetropic eye was employed in this instrument. The hand-held telescope is connected to the dichroic mirror, M_3 , by a $2:1$ angular reduction linkage. The fundus lesion is viewed through the telescope, and the aiming spot is focused upon the area. The firing button is located on the telescope mount, so that it may be easily depressed for firing. This button actuates a microswitch that opens a shutter during the period while the button is depressed. The argon beam passes through the shutter into the optical system to be eventually deflected by the mirror, M_3 , into the patient's eye.

The one-third power telescope is conveniently manoeuvrable and is capable of viewing an area 80° of arc in an axis parallel with the optical head and 160° perpendicular to it. Inherent reflective deficiencies in the M_3 dichroic mirror at extreme angles restrict adequate laser treatment in these regions. Visual inspection of the ocular fundus, however, is unimpaired throughout this cone of movement. The telescope can be focused on any portion of the intraocular structures by rotating its head. In this manner, the refractive error of the patient can be optically neutralized within a substantial correction range of -12 to $+18$ diopters. The colour balance of the fundus image is excellent, although a slight shift toward the red portion of the spectrum is evident due to elimination and reflection of the blue-green rays from the eye by the dichroic mirror M_3 .

(5) Special laser optics

DICHROIC MIRRORS

The effectiveness of the multilayer mirrors M_1 , M_2 , and M_3 , greatly influences the performance of the instrument. The idealized transmittance curves, shown in Fig. 4, display the desired characteristics of each mirror, while the actual measured transmittance curves for the multi-layer mirrors vary somewhat from the ideal. Preservation of the colour balance

FIG. 4 Idealized transmittance curves of three dichroic mirrors— M_1 , M_2 , M_3 —incorporated in optical head of argon laser intraocular photocoagulator. Shaded area indicates the acceptable tolerance for the dichroic mirror

of the observed retinal image was attempted by retaining as much visible light as possible outside the argon band in the aiming and viewing beams. Mirror M_1 must transmit highly the argon laser wavelengths (4579–5145Å), especially the principal wavelength at 4880Å and 5145Å, and reflect the rest of the visible spectrum, *i.e.* the target beam. Mirror M_2 must transmit the argon laser beam highly, and reflect 50 per cent. of the illuminating beam. Mirror M_3 must reflect the argon laser wavelengths entirely and transmit 50 per cent. of the remainder of the spectrum at all angles between 15 and 55° of beam incidence, *i.e.* reflect 50 per cent. of the target and illuminating beam into the patient's eye and transmit 50 per cent. of the light from the fundus into the observer's eye. The scattering factor of mirror M_3 was kept much below 0.5 per cent. since the scattering potentials of visible light, and especially of the argon beam, could decrease the contrast of the fundus image markedly.

DIFFUSERS

The beam-spread of a typical argon laser assumes a Gaussian-shaped distribution with gradual fall-off of energy with increasing angle from the axis. The retinal impact of a low energy laser beam might create a coagulation smaller than a higher energy beam, because only the peak of the beam's energy is used in the former case. Also, higher energy radiation will heat the tissue surrounding the target spot by thermal conduction, and the greater the energy in the spot, the larger will be the affected area.

The above situations lead to a heat distribution which is highly concentrated at the centre of the lesion relative to the edge. In order to provide a more uniform energy distribution with lesion diameters up to 5°, to concentrate the laser energy at the retina rather than the pupillary plane, and to avoid the concentration of energy near a mirror or lens in the optical system, it was necessary to insert a diffuser between the laser beam and the first telescope lens. The diffuser destroys some of the collimation as well as the spatial coherence of the beam, but does produce a fairly uniform energy intensity across the burn diameter. The various burn sizes can be produced by interposing the appropriate diffuser and its associated field stop on the optical axis at a position conjugate to the patient's pupil. Since the argon laser beam is 4 mm. in diameter at the diffuser, the 0.7 magnification of the optical system reduces the laser beam diameter at the patient's pupil to about 3 mm. This diameter is small enough to pass easily through a dilated pupil and large enough to give a low energy density at the pupillary plane.

Photocoagulation procedure

The patient is treated in the reclining position with the optical head positioned in the approximate meridian of the intraocular lesion. The background viewing light is directed through the dilated pupil and the appropriate target beam is selected and focused. The laser power is attenuated to a low level and gradually raised until the proper coagulation reaction is observed. The remainder of the photocoagulation procedure is performed in the manner that has become routine with other continuous sources such as the xenon-arc lamp.

(B) Biomicroscopic delivery system. For anterior segment photocoagulation

The utilization of a biomicroscope as a delivery system to transport a laser beam from its source to the eye has several distinct advantages.

- (1) The target area can be viewed binocularly and stereoscopically.
- (2) The target tissue can be viewed with varying powers of magnification.

- (3) Pre-corneal and contact lenses can be used with the biomicroscope for examination of the fundus or anterior chamber angle.
- (4) A moderate degree of mobility is available with the biomicroscope that enables photocoagulation to be performed with some versatility.
- (5) Photographic systems can be adapted to some biomicroscopes (Zeiss) that allow concurrent recordings of photocoagulation procedures.
- (6) The biomicroscope has distinct advantages over any other existing observation system for anterior segment photocoagulation.

The biomicroscope delivery system was fabricated and assembled at the Bell Telephone Laboratories, Murray Hill, New Jersey. The basic design of the beam-splitter type of "slit-lamp" biomicroscope* was modified to accommodate the argon laser beam without appreciable power losses at the optical components and with maximum safety for the surgeon. The unmodified beam splitter mount is constructed with two viewing or photographic systems available in addition to the surgeon's observation system. This beam splitter "splits" the rays of light from the patient's eye into two parts—one entering the surgeon's eyes at the eye pieces and the other entering the secondary observation tube or camera. Our fundamental conceptual shift of design was to coat one of the beam splitter cubes so that it would deflect the laser beam *into* the patient's eye for photocoagulation,

FIG. 5 Diagram of biomicroscopic delivery system for anterior segment (and selected paramacular) photocoagulation with argon laser radiation. The beam passes through a triggered shutter and relay system to the beam splitter cube. The dichroic diagonal face of the cube reflects the argon beam through the magnification selector to the patient's eye. Simultaneous examination and photography are performed through protective anti-argon filters

* Manufactured by Carl Zeiss, Inc., of Oberkochen, West Germany

while retaining the other beam splitter cube for photographic purposes. In addition, the observation system for the surgeon was altered slightly so that the view of the target area continued to be sharp and bright despite the elimination of the argon spectrum.

The Zeiss beam splitter accessory was dismantled and the entirely new beam splitter cubes were introduced (Fig. 5). One of these cubes was specifically coated on sides 4, 5, and 6 with an antireflection coating. The intra-cube diagonal splitter face, 3, was coated with a dichroic film that reflected the argon wavelengths highly and allowed high transmission of the rest of the visible spectrum. The faces of the cubes nearest the observer, sides 1 and 2, were covered with an anti-argon spectral film to prevent the entrance of any stray argon energy into the observer's eye.

The argon beam is introduced into the beam splitter from the laser or intermediate articulated-arm delivery system (with adapter) and is deflected away from the observer through the telescopic-magnification selector, toward the objective lens of the slit lamp, as shown in Figs 5 and 6. The objective lens (100–200 mm. focal length) then focuses the beam on the target tissue. This tissue can be located externally, in the anterior segment, in the region of the trabecula or in the fundus of the eye. The latter two ocular areas require the ancillary use of a contact lens (Goldmann, Thorpe, or Worst lenses) or a pre-corneal lens (Hruby, Rubin) to achieve the proper focus. The addition of a -1 or -2 dioptre lens before the delivery system inlet, or the movement of the oculars away from proper adjustment, will create a disparity between the focus of the observation system and the argon photocoagulation system. This manoeuvre will permit a larger coagulation spot to be produced by the unfocused beam when this is desired. Generally, the biomicro-

FIG. 6 *Biomicroscopic delivery system during argon laser photocoagulation, showing articulated-arm relay system, adapter, and slit-lamp in an operational attitude*

scope is utilized because of its ability to cauterize minute areas, and the purposeful defocusing of the argon beam is not usually employed.

The focusing precision of the beam can be enhanced even further by the use of the higher power telescopic couplets in the magnification portion of the microscope ($25\times$, $40\times$). The higher the magnification, the more shallow will be the depth of focus and therefore the depth of the coagulation. By employing higher power couplets in this manner, extremely precise coagulations on the order of 0.001 cu. mm. can be produced.

Before actual photocoagulation, a highly attenuated argon beam is transmitted through the instrument and directed upon the target. Since the inspection and photocoagulation optical systems are the same, the beam can be brought to a sharp focus by simply manipulating the slit lamp until the target tissue is clearly seen. A foot or hand trigger is then pressed that electrically removes the attenuating neutral density filter from the path of the beam. The full predetermined power of the argon beam then travels through the delivery system to the coagulation site. The length of each burst of light can be regulated by a precise shutter mechanism or can be controlled manually to create the desired photocoagulation effect. Although the observer's eyes are protected from the argon radiation, all aspects of the photocoagulation process can be observed without difficulty. Simultaneous cinematography during the coagulations has been a valuable documentary procedure.

(C) Articulated-arm delivery system. For surface photocoagulation

The need to construct a system that would transmit the laser beam through a flexible, easily movable mount has been apparent for several years. A new device has been developed that guides the beam from the laser source through hollow, jointed arms to a small handle. The handle is approximately the size of a fountain pen and can be moved easily in any direction by the surgeon. The handle can be attached to a surgical biomicroscope for anterior segment work. In this case, the beam is transmitted through the jointed arms of the delivery device, introduced into the optical system of the microscope, and directed upon the target tissue by the biomicroscopist.

FIG. 7 Diagram of articulated-arm delivery system for surface photocoagulation with argon radiation. The beam is reflected by the prisms and focused on the tissue by the convex lens in the handle. The lens may be removed and replaced by an adapter for use as a relay system with the biomicroscope and monocular indirect photocoagulator

The articulated-arm delivery device was machined and assembled at the Bell Telephone Laboratories, Murray Hill, New Jersey. Members of the staff who aided in development of the system are D. R. Herriott, E. I. Gordon, D. A. S. Hale, and W. Gronros.

The system consists of an alternating series of six hollow tubular sections and six hollow blocks (Fig. 7). The tubes are connected to the blocks at right angles to each other so that they form an elbow. Prisms within the blocks reflect the laser beam around each 90° corner. The tubular sections are constructed of inner and outer magnesium tubes. One tube is connected to the block on one end and the other tube to the block at the opposite end. Ball bearings set between inner and outer tubes allow free rotation about a common axis. The net result is that the arm, which resembles a series of "L's" strung together, has full tri-dimensional mobility.

Because the tubes swivel and the corners remain rigid, the light always makes 90° turns. After it has been reflected through the tubes, the light passes out through the small pen-like handle. The coherence and collimation of the laser beam is preserved by the high quality reflective characteristics of the prisms. Thus, with these properties maintained, the light can be focused to an exceedingly small spot by the photocoagulation instrument. The handle of the articulated-arm can be attached with the proper adapter to any of the photocoagulation devices—the optical portion of the intraocular photocoagulator, the biomicroscope, or the modified monocular indirect ophthalmoscope head. By incorporating the articulated arm as an intermediate delivery system, each of these photocoagulation devices is capable of extreme manoeuvrability and flexibility. Critical adjustments, observation, and focusing through these instruments are performed much more precisely, more rapidly, and with greater ease.

The addition of a 30 dioptre lens to the tip of the handle focuses the light to a point-sized image 33 mm. away. With this arrangement, the articulated-arm is converted into a highly effective "light knife" that can incise any animal tissue, as shown in Fig. 8. Animal and clinical testing has demonstrated that complete surgical procedures can be done without the loss of blood. The cutting ability and remarkable haemostatic qualities of the articulated photon scalpel are fascinating, the former directly dependent upon the focused power density of the beam and the latter upon the shortness of the radiation wave-

FIG. 8 *Articulated-arm delivery system being used as a "light-knife" or "photon-scalpel" for photocoagulation and incision of surface tissues*

FIG. 9 Modified monocular indirect delivery system, showing articulated-arm, jacket containing lens disc and beam splitter, and monocular indirect ophthalmoscope

FIG. 10 Diagram of optical components of monocular indirect delivery system, demonstrating relationship of ophthalmoscope, beam splitter, lens disc, and articulated-arm

length. The articulated-arm system can be used, with the proper modifications, with both pulsed and continuous wave lasers of any visible wave-length, and is the most versatile of the delivery systems developed.

(D) **Modified monocular indirect delivery system**

The recently introduced American Optical Monocular Indirect Ophthalmoscope was used as the basis for a new, highly manoeuvrable photocoagulation system. The viewing telescope, fundus illumination source, and miscellaneous optical devices were incorporated without change into a tightly fitting rectangular metal jacket (Fig. 9, page 321). This jacket holds a 70 per cent. beam splitter at a 45° attitude directly in front of the objective of the monocular ophthalmoscope. The beam splitter reflects the incoming argon beam at 90° in a direction co-axial with the optical line of the ophthalmoscope (Fig. 10, page 321). The beam can be focused through vergences of -10 to +9 dioptres by a rotary lens dismounted over the entrance port. With this arrangement, the laser beam can be concentrated on a lesion, giving a clear view of the background features.

The argon beam is conducted to the ophthalmoscopic head by the articulated arm delivery system, thereby providing exceptional mobility for difficult photocoagulation angles. A trigger gate, consisting of an electrically removable neutral density attenuation filter, is placed between the continuous-wave laser and the inlet port of the articulated arm. The attenuated laser beam, produced with the filter dropped into position, is used for preliminary focusing and aiming. Actual photocoagulation can be accomplished by raising the filter in the trigger gate, so allowing the full power of the radiation to pass into the delivery system.

Various impact sizes can be produced by defocusing the beam with the rotary lenses. In contrast, the smallest, highest power density coagulation spot can be obtained by precisely focusing the laser beam upon the lesion. The continuous nature of these lasers permits their use for any coagulation interval at the discretion of the surgeon. These features—the manoeuvrability, interval dosage control by the surgeon, focusable viewing and coagulation systems, and bright, highly contrasted illumination and target beams—make this instrument the most useful and technically uncomplicated of the intraocular photocoagulation devices.

Summary

Four new photocoagulation delivery systems have been introduced, utilizing different optical construction and designed specifically for various ocular regions. All instruments employ reliable co-axial target beams, focusable inspection and coagulation systems, and methods of beam and hazard control. The devices have been designed to incorporate manoeuvrability, high magnification, low beam transmission losses, high optical resolution, and versatility in performance where these features are considered desirable.

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