STUDIES IN PHOTOCOAGULATION

I. THE PHOTOCOAGULATING BEAM*

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PHOTOCOAGULATION has become an important method of treatment for several eye conditions. It requires the introduction into the patient's eye of a certain amount of energy, concentrated into a small area of the fundus. Simultaneous fundus observation is also necessary. In addition, before photocoagulation is applied, a target mark should be visible on the pigment epithelium, exactly at the spot where the energy is to be concentrated. Any photocoagulator must, therefore, have two essential components, a photocoagulating beam and an observation system. The first article of this series is a study of the photocoagulating beam; in the second article problems related to the observation system will be discussed; the third will describe the physical nature and properties of the laser beam; and in the fourth a detailed solution will be presented for the use of a laser beam in photocoagulation.

(1) BASIC REQUIREMENTS OF A PHOTOCOAGULATING BEAM

As the photocoagulating energy is to be concentrated on the pigment epithelium, the beam carrying it must be focused on this structure by the optical system of the eye. For example, if the eye is emmetropic, the beam is to be collimated before it penetrates the cornea. The cross-section of this beam at the entrance of the patient's pupil must not exceed the pupillary size, that is a maximum of about 8 mm. in diameter. Such a beam could be provided by a light source located at the focus of a corrected photographic objective. It is well known that, under these conditions, only a point source will produce a perfectly parallel beam. In the case of an extended source, each point of the source will produce a parallel beam, but these beams will not be parallel to each other. The resulting total beam will display a divergence (D) by the ratio:

$$D = \frac{r}{F} \quad (1)$$

where r is the radius of the source and F the focal length of the objective. As Formula (1) indicates, the divergence of the beam depends from two parameters: the radius of the source, and the focal length of the objective. A small divergence requires a small radius of the source and a long focal length of the objective.

The patient's eye cannot be placed in the immediate vicinity of the objective; therefore, the increase in diameter of the cross-section of the beam, due to its divergence, must be taken into account. The cross-section of the beam, at its exit from the objective, must be smaller than the patient's pupil (8 mm.). For a given distance

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If we call G the divergence of the coagulating beam, the Formula (1) becomes:

$$G = \frac{i}{2L} \quad . \quad . \quad . \quad . \quad . \quad (1')$$

As the emmetropic eye has a focal length of 17 mm., the diameter d of the retinal image will be:

$$d=17G \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Let us assume that the average size for the retinal image of the coagulating beam is 1 mm. The burn produced by it would be somewhat smaller because of the cooling effect of the blood circulation. In this case the divergence G is expressed as follows:

$$G = \frac{1}{17} = .0588 \quad . \quad . \quad . \quad . \quad (4')$$

The above set of four equations with five unknowns, A , B , G , L , and i , gives us one degree of freedom to determine either one of the unknowns, or a ratio between two of them. Practically, the value of any of the unknowns can vary within narrow limits only. If one assigns a numerical value outside these limits to one of the unknowns, impractical values will result for the other unknowns.

(2) EXPERIMENTAL DATA

The first really practical photocoagulator was made by Zeiss (Meyer-Schwickerath, 1959). It utilizes a xenon arc lamp of 2,000 watts which may be overloaded to 3,000 watts. The firing of this lamp requires a tension of 30,000 volts. The necessity of insulating electrically the 30,000-volt circuits has forced the constructor to build the power supply in the same housing as the lamp. Another problem was the need to dissipate the heat resulting from a radiating source of 2,000 Joules, or 500 calories per second. These two factors made it necessary to use an extremely heavy and bulky housing for the lamp and its power supply. The volume and weight of the instrument made it cumbersome, and it appeared useful, therefore, to attempt to improve its versatility. We have investigated two types of arc lamp for this purpose: mercury arcs and xenon arcs.

(A) **Results obtained with Mercury Arc Lamps.**—A pilot model of a very simple photocoagulator, using a mercury arc lamp of 250 watts, was tried successfully in rabbit eyes but did not have enough energy to give consistent results in human eyes (Brockhurst, Wolf, and Schepens, 1959). C. J. Koester, from the American Optical Company, rebuilt this photocoagulator and used a 100-watt mercury arc lamp. By a very ingenious optical system, he gathered almost all the energy radiated by this small source. Heating problems became negligible and a small fan sufficed for cooling the instrument which was very compact. Another advantage of the small source was that the power supply did not have to be housed with the light source, as it was quite easy to connect the two units with light adequately-insulated electrical wires.

A series of trials was performed with this instrument, in rabbit as well as in human eyes. In the pigmented rabbit eye, a burn of moderate intensity could be obtained with a 6° aperture of the diaphragm and an exposure time of 1 second. Tissue explosion occurred with an exposure time of 5 seconds. This instrument was used

for the treatment of eighteen human eyes. In all cases, the diaphragm of the instrument was open to 6° and the patient's pupil measured from 6 to 8 mm. In eight cases, the photocoagulator was used with its normal electrical load. The results are summarized in Table I (compiled by F. Sabates).

TABLE I
RESULTS OBTAINED WITH A 100-WATT MERCURY ARC PHOTOCOAGULATOR
NORMAL ELECTRICAL LOAD

Case No.	Media		Refraction		Exposure Time (sec.)		Result
	Clear	Hazy	Emmetropic	Ametropic	Maximum	Minimum Causing Burn	
12,457	✓		✓		0.5		No burn
12,512		+		+11 D	1.0		No burn
12,514		+		(Application on buckle)	2.5		No burn
12,540		+	✓		3.0		No burn
12,413	✓		✓		5.0		No burn
12,446	✓		✓			0.5	
12,473	✓		✓			1.5	
12,504		+	✓			5.0	

It appears from these data that, when all conditions were favourable (pupil widely dilated, clear media, and no refractive error), a burn could be obtained with an exposure of 0.5 to 1.5 seconds. However, in one case with a lightly-pigmented fundus no burn could be obtained under these ideal conditions with an exposure of 5 seconds. When the media were hazy or the ametropia large, no burn was obtained with an exposure of 1 to 3 seconds. We concluded that insufficient power was available.

Because of this inadequacy another set of trials was made after overloading the mercury lamp by about 30 per cent. The results obtained in ten cases are summarized in Table II (compiled by F. Sabates).

TABLE II
RESULTS OBTAINED WITH A 100-WATT MERCURY ARC PHOTOCOAGULATOR
ELECTRICAL OVERLOAD

Case No.	Media		Refraction		Exposure Time (sec.)		Result
	Clear	Hazy	Emmetropic	Ametropic	Maximum	Minimum Causing Burn	
4,852		++	✓		2		No burn
12,582	✓		✓			0.5	
12,601	✓			-6.00		1.0	
10,756		++	✓			2.0	
12,561	✓		✓			2.0	
4,252	✓		✓			2.0	
12,568		+		(Application on buckle)		3.0	
6,226	✓			-6.00		3.0	
12,669	✓		✓			4.0	
12,532	✓			-13.00		5.0	

With the electrical overload, a higher percentage of visible burns was observed. However, the exposure time required was between 0.5 and 5 seconds, which is too long. Under favourable circumstances, as when the burn had to be placed anterior to the equator, it was often impossible to obtain the desired effect even with a 5-second exposure time. It was felt, therefore, that this instrument had a severe basic defect, namely that maximum amount of energy available for photocoagulation was insufficient.

(B) Results obtained with Xenon Arc Lamps.—A more promising solution to this problem was obtained by using a 300-watt compact xenon arc lamp, an apparatus which is still being developed in the laboratories of the Retina Foundation (Schepens, 1962). Its main feature is a special power supply system, designed and built by David Griffin. As represented in Fig. 2, the power supply of this photocoagulator is composed of five functional units:

- (1) 300-watt compact xenon arc lamp, cooled by forced air.
- (2) Ignitor.
- (3) 60-watt power supply.
- (4) Variable high power pulse supply.
- (5) Transistorized timing control circuit.

FIG. 2.—Diagram of power supply of new xenon arc photocoagulator.

Unit 1.—The lamp used is the Hanovia 300-watt, 15–20-volt, D.C., No. 914 C-1. It is run at the reduced power of 60 watts, which provides convenient illumination of the fundus thus eliminating the necessity of using an attenuating diaphragm. At 60 watts, the radiation is only 15 calories per second. This small amount of heat can be dissipated by means of a blower which is started as soon as the arc lamp is turned on. A vane-operated micro-switch is used to monitor the air flow, and a relay Ry_1 cuts the arc current if this flow is absent. The xenon arc lamp can be flashed from 60 watts to over 900 watts for the duration of a photocoagulation. As the average heat to be dissipated is maintained far below 300 watts, no heat damage is caused to the equipment. It is easy to separate the xenon arc unit from the other units of the photocoagulator, and this gives the apparatus a versatility which cannot be obtained when all the units must be built in one housing, as in the Zeiss instrument.

Unit 2.—The ignitor circuit is turned on by means of a push button P_1 . Depression of this button causes the latching relay Ry_2 to set, and it completes the primary ignitor circuit through the limiting resistor R_1 , and the coil shunted by a spark gap. The current through the ignited xenon lamp causes relay Ry_3 to pick up, which in turn resets Ry_2 cutting off the ignitor circuit.

Unit 3.—The arc is maintained at the 60-watt level by a 3-amp., 20-volt, D.C. power supply, filtered through R_2C_2 . The same power supply filtered through R_3C_3 is used for the timing circuit.

Unit 4.—A variable output, intermittent duty, D.C. power supply furnishes the additional current necessary for photocoagulation. The variable power is obtained by changing the primary voltage in the power supply transformer through an autotransformer in series. The peak current to be supplied is about 45 amps.

Unit 5.—A transistorized timing-circuit switches the high power supply on through a relay Ry_5 . Push button P_2 , or a remote push button P_3 , causes the relay Ry_4 to pick up. Thus, the capacitor C_4 is switched on across the power supply, and charged up. When the button P_2 or P_3 is released, the fully-charged capacitor C_4 is put across the base circuit of a transistor TR. The transistor TR then turns on and stays until C_4 is discharged through its base circuit, in which the variable resistor R_4 serves to control the time of discharge. Relay Ry_5 in the collector-circuit operates the contacting of the high power supply. The timing-circuit permits to pulse the xenon arc to a predetermined high level of energy. Whenever desired, the timing may be manually controlled.

The power supply system seems to meet most of the requirements of a photo-coagulating source. The low operating voltage simplifies the problem of cooling and insulating. A high luminance by unit area of source is produced by flashing the arc at a high power level. The electronic timer offers accurate control of the exposure time. The physical separation between the xenon arc unit and the other units makes the instrument very versatile. The power supply, composed of the units 2, 3, 4, and 5, occupies a volume not exceeding 4.5 cubic feet, and weighs less than 70 lb. The Zeiss instrument has a volume of about 38 cubic feet, and a weight in excess of 400 lb.

FIG. 3.—Diagram of optical system forming coagulating beam in new xenon arc photocoagulator.

The optical system of the coagulator (Fig. 3) is composed of a wide-angle condenser, an objective, and a 100 per cent. front surface mirror. The condenser, computed by one of us (O.P.), is composed of five elements, three of which are doublets. The angular aperture of the condenser is $32^{\circ} 53'$ (half angle), and the aperture of the light beam leaving the condenser is $4^{\circ} 46'$. This means that, if the size of the source is 0.4 mm. in diameter, the size of the image formed by the condenser is about 2.80 mm. This image is formed at 420 mm. from the condenser's last lens surface. A diaphragm is located in the image plane to limit the size of the image. By the same token, the diaphragm limits the portion of the source admitted in its aperture, and this controls the light intensity available for photocoagulation. The objective used is a Wollensack, 50 mm. focal length, $F/4.5$. It is so located that the image of the source coincides with its principal focal plane. The objective is also provided with a diaphragm, which limits the diameter of the coagulating beam. If the first diaphragm is open to 2.8 mm., Formula 1 gives the divergence of the coagulating beam:

$$D = \frac{1.4}{50} = 0.028.$$

When used on an emmetropic eye, which has a focal length of 17 mm., the size of the retinal image is: $2 \times 0.028 \times 17$ mm. or approximately 1.00 mm. Thus, the size of the retinal image depends on the aperture of the first diaphragm. The objective is axially adjustable, which helps in compensating refractive errors of the patient's eye.

Tests with our apparatus on pigmented rabbits have shown that, with short exposure times and reduced wattage, it is easy to obtain adequate burns. Haemorrhage and tissue explosion have been caused by exposure of less than 1 second, and using only a fraction of the total energy available. Preliminary tests on man have indicated that, with short exposure times, the instrument can deliver sufficient energy to obtain adequate burns.

There is one problem in the above instrument which is only partly solved, namely that of keeping the arc in a stable position when the wattage is increased from 60 watts to a higher level. Work on this question is still in progress. Because of this difficulty, it is necessary to keep the instrument's first diaphragm open, which makes

it impossible to obtain a retinal burn covering a very small area. On the other hand, if the diaphragm is not kept open, displacement of the arc may cause the image of its crater (located near the negative pole) to be located outside the diaphragm's opening. With a fully-open diaphragm it is easy, in this instrument, to control the power level by changing the power load of the arc between 60 and 900 watts.

Summary

Problems encountered in the design of a coagulating beam are examined. The characteristics of the optical components needed are analysed. Several existing types of coagulators are studied, and a new solution of this problem is presented.

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