USE OF THE NEODYMIUM:YAG LASER TO CREATE IRIDOTOMIES IN MONKEYS AND HUMANS*

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INTRODUCTION

THE ARGON LASER HAS PROVIDED THE OPHTHALMOLOGIST A MEANS BY WHICH HE can easily and rapidly produce an iridotomy for the treatment of angle-closure glaucoma. Although it is a relatively simple procedure, in most cases numerous applications are required before completing a satisfactory iridotomy, and it is extremely difficult to treat some eyes with very dark brown or light blue irides.[1,2] A laser that could safely and reliably make an iridotomy with a single pulse would certainly be a major advance.

Early studies with the Q-switched ruby (Q-ruby) laser showed great promise and using this technique one could readily and consistently produce a patent iridotomy in monkey and human eyes with a single pulse.[3-5] Like the Q-ruby laser, the Q-switched neodymium-YAG (Q-Nd:YAG) laser builds up a large quantity of energy that is released as a short pulse of light, lasting 10 to 20 nsec, and having a peak power capacity of several hundred thousand kilowatts. Unlike long-pulsed lasers, Q-switched lasers cause photodisruption and can mechanically punch or tear open a hole in the iris with a single pulse. The Q-ruby laser is a large and unwieldy instrument that has never reached the point of industrial production. The Q-Nd:YAG laser, on the other hand, has enjoyed a

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high degree of industrial refinement and numerous production models are now available for investigation. It has already proved to be of value as a useful technique to create a capsulotomy and it seemed reasonable that the same photodisruptive process might produce an iridotomy with a single pulse, as has been shown by Fankhauser.[6] The current study was undertaken to investigate this technique in monkeys and humans.

MATERIALS AND METHODS

The Coherent JK prototype Nd:YAG laser and the American Medical Optics (AMO) YAG-100 laser were used throughout these studies. The Coherent laser had a maximum energy output of 6 mJ, could produce a pulse-train of up to 9 bursts each separated by 20 msec, and converged the laser beam to 100 μ in air. Our model of the AMO laser had a maximum energy output of 20 mJ, delivered only by single bursts and converged its beam to 25 μ in air.

CYNOMOLGUS MONKEYS

Preoperative and final evaluation of each of four monkeys included biomicroscopy, gonioscopy, dilated fundus examination, and measurement of intraocular pressure (IOP) using the Alcon Pneumotonograph. Photographs of the anterior segment and posterior pole of each monkey were also taken.

Prior to laser treatment, one drop of 2% pilocarpine was instilled in the cul-de-sac, following which a laser iridotomy was made in each eye at 10, 2, and 6 o'clock. The right eyes of two monkeys were treated with the Coherent laser, using 4 and 6 mJ and a pulse-train of 1, 5, and 9 in each of the three iris locations. The left eye was treated in a similar manner 21 days later.

The right eyes of two monkeys were treated with the AMO laser, using single bursts ranging from 10 to 20 mJ at 2 mJ step intervals, until all six locations in these two right eyes were treated. The left eye of these two monkeys were treated similarly 21 days later.

Two days prior to enucleation a complete examination was made including fluorescein angiography. On day 30 both the right and left eyes were enucleated and the anterior segments were placed in 4% glutaraldehyde solution buffered with 0.1 N sodium cacodylate. The entire cornea in each of eight eyes was trephined and prepared for scanning electron microscopy (SEM). Endothelial cell counts were taken in the treated area and in the adjacent untreated cornea. Six iris specimens that included an iridotomy from left eyes and two from right eyes were prepared

for transmission electron microscopy (TEM). The lenses in each eye were examined grossly for opacities beneath the laser-treated areas. One opacity was photographed grossly and submitted for phase contrast microscopy. All other lens specimens were examined by light microscopy. Each posterior segment was examined grossly for evidence of laser damage, following which the posterior poles were sectioned for light microscopy.

HUMAN STUDIES

Twenty-one patients with bilateral primary chronic angle-closure glaucoma were enrolled in a prospective study. An argon laser iridotomy was performed in one randomly selected eye and a Nd:YAG laser iridotomy was performed in the fellow eye.

Prior to laser therapy every patient underwent a complete ophthalmic examination and bilateral wide-field specular microscopy. Each patient was prescribed 1% prednisolone acetate four times daily, starting 1 day prior to treatment, and this was continued for 7 days after treatment. Pilocarpine hydrochloride of varying strengths was used by every patient without change throughout the study.

Argon laser iridotomies were performed in the conventional way, using an Abraham contact lens and with settings of 0.2 seconds, 50 μ, and 1000 mW of power. Repeated, well-focused burns were made until at least 100 μ of anterior lens capsule were seen through the iridotomy.

A coated Nd:YAG contact lens was used with the Nd:YAG laser. A site in the midperipheral supranasal or supratemporal quadrant was selected. When using the AMO laser, we selected an energy setting varying from 10 to 15 mJ. With the Coherent laser, we began with a single burst of 5 mJ and, if additional pulses were required to complete an iridotomy, they were delivered as a pulse-train of 3. Following treatment, the eye was carefully observed at the biomicroscope in order to detect possible damage to the cornea, anterior chamber, iris, and lens.

In all cases both eyes were treated during the same visit with an interval of 5 to 10 minutes between eyes. Both eyes were observed at hourly intervals for 3 hours after treatment. Each patient returned for a follow-up visit at 1 day, 1 week, and 1 month after treatment. The eye was carefully examined during each visit with particular attention being paid to the Snellen visual acuity, applanation tonometry, anterior segment inflammation, and the status of the cornea, iris, and lens. If an iridotomy closed so that its minimal diameter was less than 75 μ, using either technique, further treatment was performed to enlarge it or create a new one.

One month postoperatively the pupils were dilated with 1% tropica-

TABLE I: SIZE OF IRIDOTOMY FOLLOWING SINGLE PULSE OR PULSE-TRAIN WITH THE Nd:YAG LASER

ENERGY* (mJ)	SINGLE PULSE (μ)	PULSE-TRAIN OF 5 (μ)	PULSE-TRAIN OF 9 (μ)
4	50†	100	150
6	0	175	200
10	375		
12	175		
14	350		
16	300		
18	50		
20	50		

*n = 2 eyes for each energy level.
†Average size of iridotomy.

mide and the patient was given a complete eye examination, including repeat specular microscopy of each eye and fluorescein angiography with the transit phase behind the iridotomy in every eye treated with the Nd:YAG laser. Late pictures were taken of both posterior poles.

Analysis of the data was performed using chi-square analysis, the Student's *t*-test, and linear regression analysis of one variable at a time. Correlation coefficients were not considered clinically significant unless they were less than 0.02.

RESULTS

ANIMAL STUDIES

A laser iridotomy was completed with a single burst or pulse-train in nearly every case. An adequate iridotomy could be obtained with a single burst of 10 to 16 mJ (Table I) and with 4 to 6 mJ and a pulse-train of 5 to 9. Although a laser iridotomy was made in every eye (Fig 1), nearly all of these had closed by the time of enucleation.

In most cases there were spottly hemorrhages on the iris surface adjacent to the iridotomy (Fig 1) and in two cases there occurred a small cascade of bleeding that ceased spontaneously within a few seconds (Fig 2). There was dispersion of pigment and iris debris and heavy flare in the anterior chamber at the end of the procedure in each case.

The IOP in each of the eight eyes was measured before and 1 hour after laser iridotomy. There was no significant increase in IOP 1 hour after treatment. Fluorescein angiography and fundus examination revealed no evidence of retinal damage.

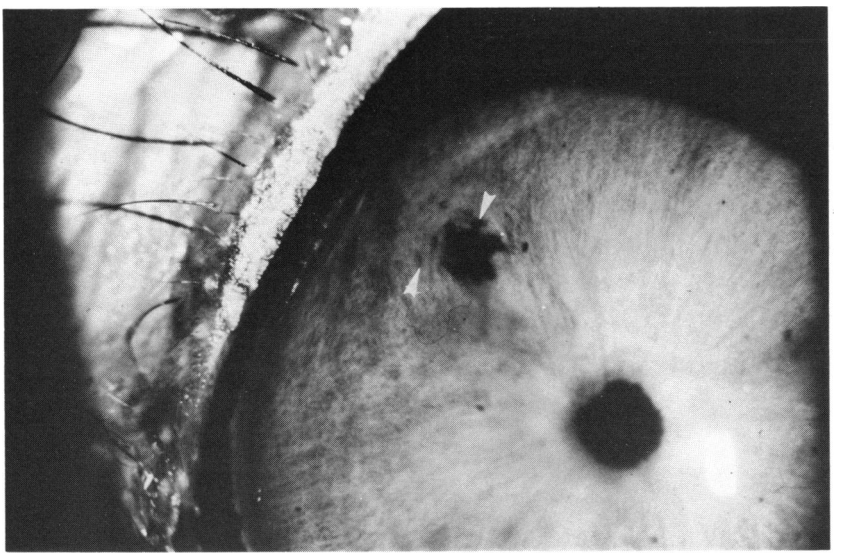

FIGURE 1
Patent Nd:YAG laser iridotomy created with 10 mJ, single pulse, in a monkey. Numerous bleeding points surround iridotomy (*arrows*).

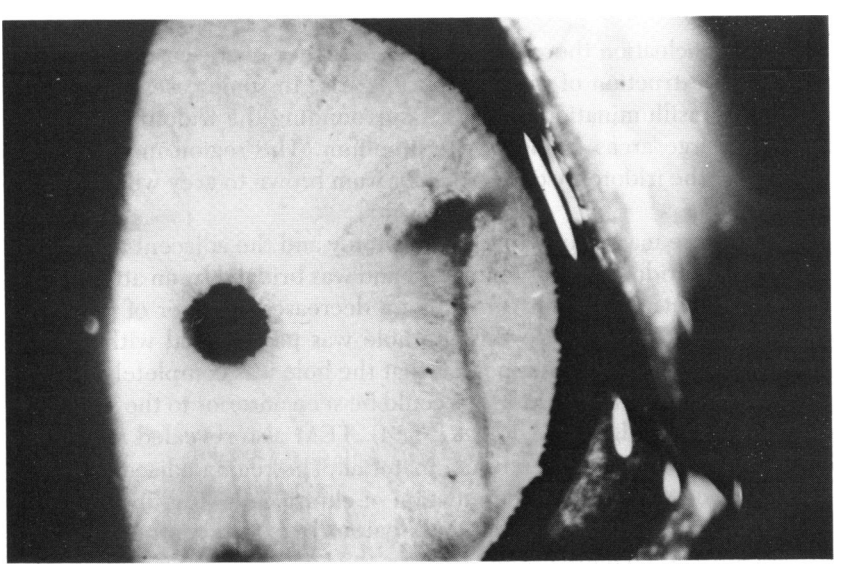

FIGURE 2
Cascade of blood from edge of a newly-created iridotomy (12 mJ, single pulse).

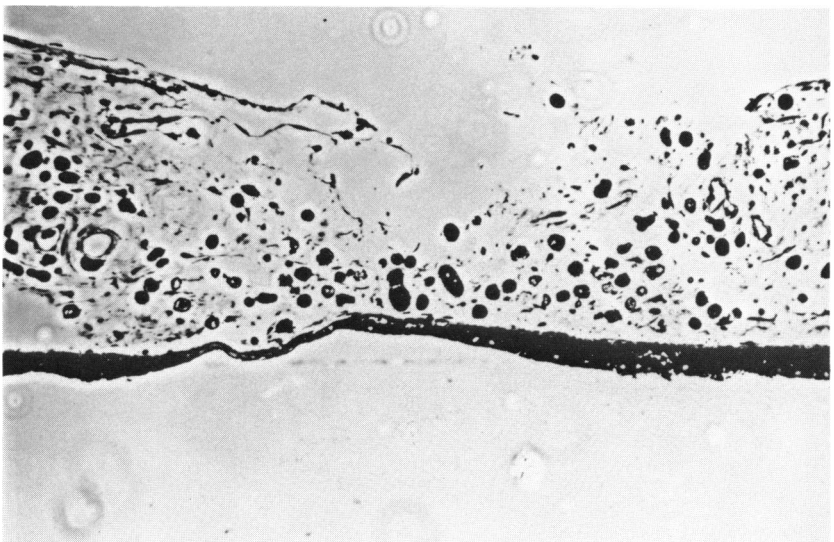

FIGURE 3
Phase contrast microscopy through an iridotomy that subsequently closed. Defect is closed by an attenuated layer of pigment epithelium, anterior to which are numerous clump cells (*arrows*) (× 200).

Prior to enucleation there was no gross evidence of any corneal opacity or unusual destruction of the surrounding iris. In some cases there was increased transillumination of the iris surrounding the iridotomy, showing loss of large areas of pigment epithelium. The region immediately surrounding the iridotomy changed color from brown to grey within 1 to 2 weeks.

Sections were made through each iridotomy and the adjacent tissue. In most cases the iridotomy was not patent and was bridged by an attenuated layer of pigment epithelium containing a decreased number of pigment granules (Fig 3). Anterior to this the hole was partly filled with clump cells. In other specimens it appeared that the hole was completely closed while stromal cells and melanocytes could be seen anterior to the pigment epithelium that bridged the defect (Fig 4). TEM also revealed scattered fibrocytes and basement membrane material. The region adjacent to the iridotomy showed a heavy accumulation of clump cells (Fig 5).

In two specimens the iridotomy was patent by phase contrast microscopy (Fig 6). The pigment epithelium was thickened at the margins of the defect and clump cells were heavily distributed in the tissue adjacent to the iridotomy.

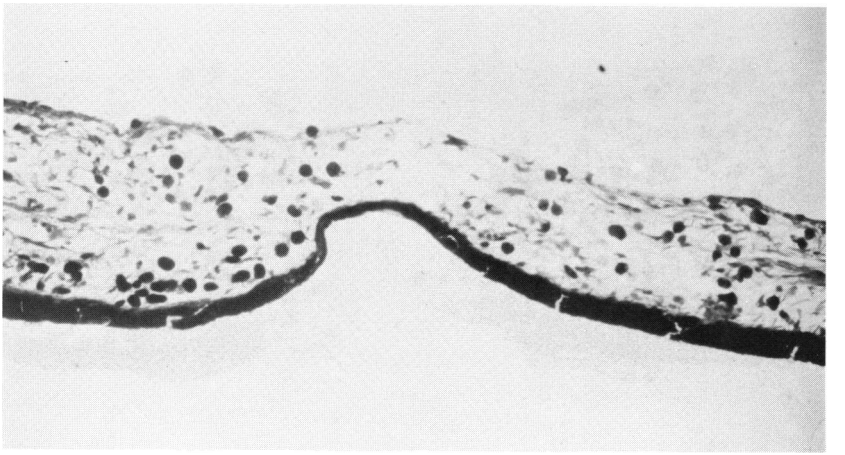

FIGURE 4
Iridotomy is bridged by an attenuated layer of pigment epithelium and markedly thinned stroma. There is a heavy accumulation of clump cells adjacent to iridotomy site (× 490).

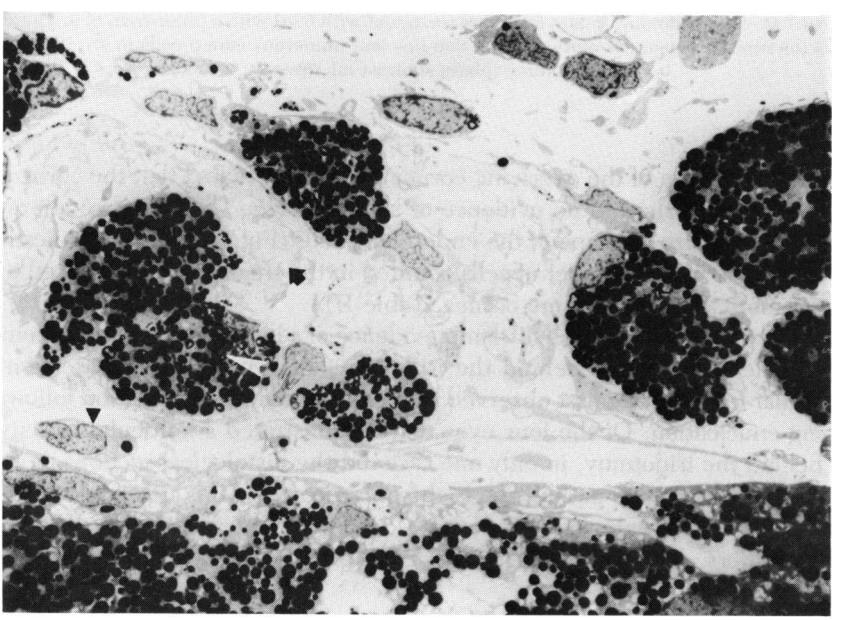

FIGURE 5
TEM through an iridotomy that subsequently closed. There are clump cells (*white arrow*) anterior to pigment epithelium along with basement membrane material (*black arrow*) and scattered fibrocytes (*black caret*) (× 2500).

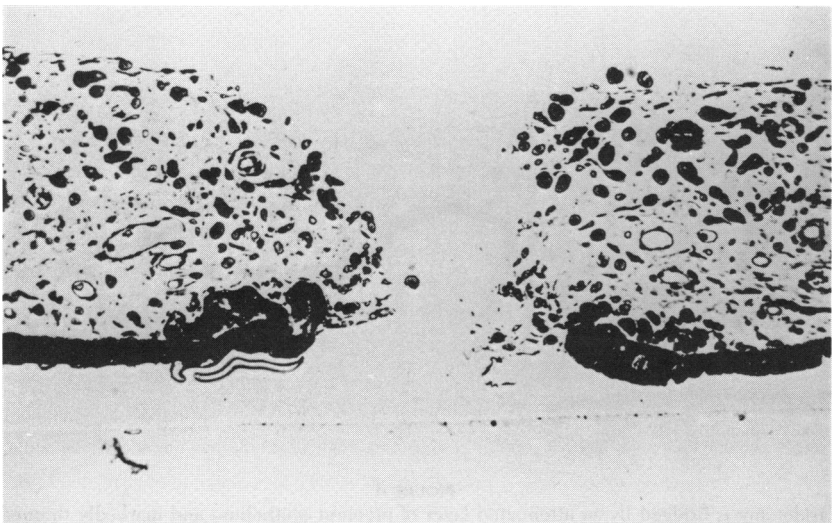

FIGURE 6
Nd:YAG laser iridotomy 9 days following treatment with 6 mJ with a pulse-train of 9. There is thickening of pigment epithelium at margins and numerous clump cells in stroma that borders iridotomy (phase contrast microscopy, × 200).

Examination of the overlying cornea by SEM revealed that the corneal endothelium showed no evidence of laser damage. There was no alteration in the size or shape of the endothelial cells (Fig 7), and no significant difference in the number of cells counted in the treated area compared to a remote area in the same cornea (Table II).

In two cases there was slit-lamp evidence of a lesion in the anterior lens capsule immediately behind the iridotomy. In two additional cases lenticular lesions were first observed by gross pathologic examination following enucleation. Of the four eyes that demonstrated a lenticular opacity behind the iridotomy, in only one case did the histological sections demonstrate lenticular pathology. Light microscopy in this case revealed a rupture of the anterior lens capsule, localized degeneration of anterior lens fibers, and hyperplasia of the lens epithelium through the capsular defect (Fig 8).

Light microscopy of the trabecular meshwork in all animals showed varying amounts of pigment, fibrin, and some cellular debris in the trabecular meshwork. Pigment was also seen within the endothelial cells lining the trabecular beams.

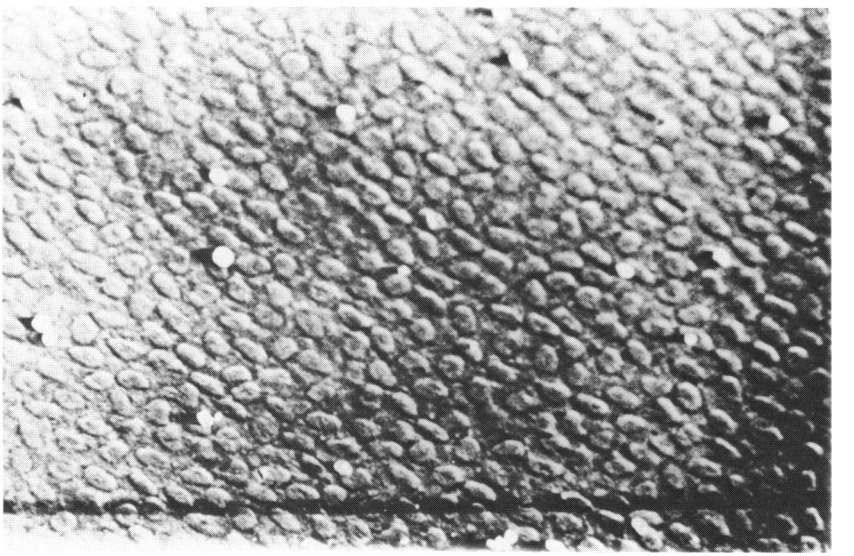

FIGURE 7
There was no alternation in size, shape, or distribution of corneal endothelial cells that lay in the path of laser beam (SEM, × 433).

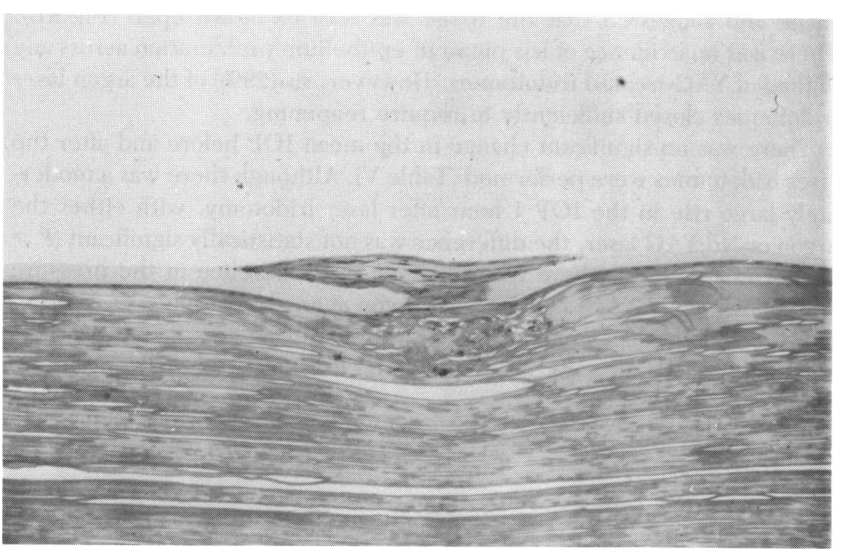

FIGURE 8
Degeneration of anterior lens fibers and hyperplasia of lens epithelium with protrusion through a defect in anterior lens capsule (H&E, × 193).

TABLE II: COMPARISON OF ENDOTHELIAL CELL COUNT IN TREATED AND UNTREATED AREAS (cells/mm^2)

MONKEY	A	B	C	D
Treated	4675	2875	3225	3730
Untreated	4627	2962	3200	3737

HUMAN STUDIES

Twenty-one patients with a mean age of 66 ± 11 years were included in the study (Table III). A mean of 48 ± 49 pulses were required for production of a patent argon laser iridotomy and this included all pulses required for retreatment. In the fellow eyes treated with the Nd:YAG laser, a mean of 3 ± 2 burns were required to create a patent iridotomy (Table IV). Much less energy was required to complete a Nd:YAG laser iridotomy and the size was generally smaller (Table IV). The edge of the typical argon laser iridotomy was rounded, and surrounded by a hyperpigmented zone (Fig 9A). The typical Nd:YAG iridotomy was irregular in shape and suggested that the tissue was torn or blown open (Fig 9B). There was no evidence of iris pigment epithelium proliferation across any of the Nd:YAG-treated iridotomies. However, six (29%) of the argon laser iridotomies closed sufficiently to require reopening.

There was no significant change in the mean IOP before and after the laser iridotomies were performed (Table V). Although there was a moderately large rise in the IOP 1 hour after laser iridotomy, with either the argon or Nd:YAG laser, the difference was not statistically significant ($P > 0.35$). Furthermore, there was no significant difference in the pressure rise following Nd:YAG, compared to argon at any time (Table V). Whereas 52% of eyes had a maximum elevation during the first hour after treatment, 44% had a maximum elevation during the second postopera-

TABLE III: DEMOGRAPHIC DATA

Sex	14 females	7 males
Race	20 Caucasian	1 black
Iris color	11 blue	10 brown

tive hour. This IOP elevation did not correlate with the preoperative IOP, the degree of postoperative intraocular inflammation, the number of Joules required for iridotomy, or with the presence of iris bleeding.

During the first 3 hours following treatment there was some inflammatory response and debris in the anterior chamber of all patients, but there was no significant difference noted between the response of those patients treated with the argon compared to the Nd:YAG laser.

Bleeding points were noted in the iris surrounding the Nd:YAG iridotomy in ten (48%) eyes. In one of these there occurred a small hyphema of less than 5%. In this case the bleeding stopped spontaneously and the hyphema was gone by the following day. Occasionally, there occurred a fine cascade of blood that ceased spontaneously.

Small localized corneal opacities were found in five argon- and seven Nd:YAG-treated eyes. The opacities in the argon-treated eyes appeared as a discreet whitening of the posterior cornea. The opacity seen following Nd:YAG laser iridotomy appeared to be either linear or annular fractures or stretch deformations of Descemet's membrane that were slightly larger in area than the iridotomy site. In two instances, there was a transient localized corneal opacity resembling the appearance of shattered glass that covered an area several times larger than the iridotomy and completely disappeared by the following day. Specular microscopy revealed greater loss of endothelial cells in the argon laser-treated eyes than eyes treated by Nd:YAG laser (Table VI).

There were focal lenticular opacities in nine (43%) argon- and no Nd:YAG-treated eyes. These appeared directly beneath the iridotomy and did not change during the course of this short follow-up. There were no ruptures or breaks in the anterior lens capsule seen in either treatment group. Posterior synechiae that distorted the pupil after dilatation were visible in three eyes treated with the argon laser.

Fluorescein angiography was satisfactorily performed in 15 argon- and 17 Nd:YAG-treated eyes. In none of these was there evidence of leakage of fluorescein, macular edema, or evidence of retinal damage in the line of laser treatment.

TABLE IV: ENERGY LEVELS REQUIRED TO ACHIEVE A SUCCESSFUL IRIDOTOMY*

	ARGON	Nd:YAG
Energy	12 ± 11 J	0.033 ± 0.025 J
No of pulses	48 ± 49	3 ± 2
Size (estimated)	200 μ	150 μ

*Mean ± standard deviation; n = 21; J = Joules.

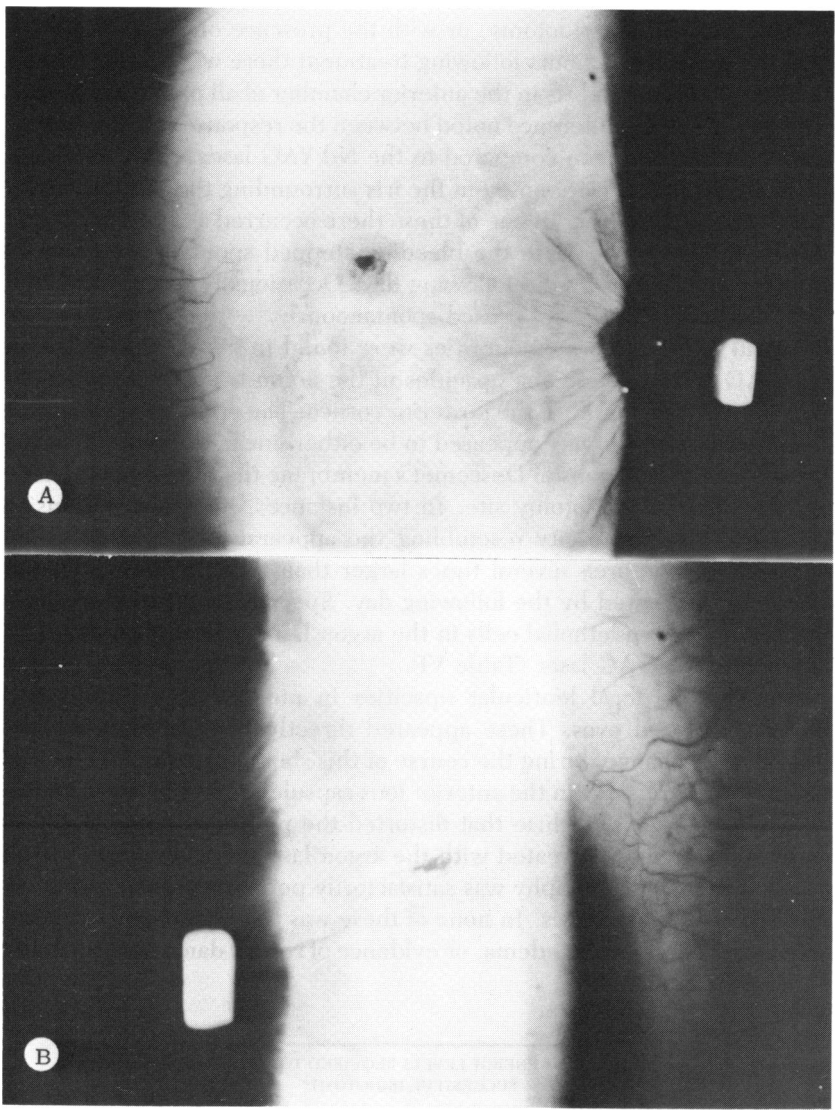

FIGURE 9
A: Patent argon laser iridotomy surrounded by a hyperpigmented ring. B: Irregularly-shaped Nd:YAG laser iridotomy surrounded by a grey zone.

TABLE V: POSTOPERATIVE RISE IN IOP*

	ARGON	Nd:YAG
Preoperative	23 ± 8	23 ± 6
Postoperative		
1 hr	29 ± 13	27 ± 9
2 hr	28 ± 15	27 ± 11
3 hr	25 ± 11	25 ± 8
1 day	18 ± 4	17 ± 5
1 mo	20 ± 7	19 ± 4

*Mean IOP ± standard deviation; n = 21.

DISCUSSION

The Q-Nd:YAG laser reliably and consistently produced a satisfactory iridotomy in all cases, using a minimum of one and a maximum of five burns in both monkey and human eyes. Iridotomies were reliably made with a single burst, using energy levels of 10 to 16 mJ with the AMO laser in monkey eyes. Smaller energy levels of 4 to 6 mJ were successfully employed with a pulse-train of 5, using the Coherent JK laser. The former laser had a spot size of 25 μ, while the latter came to focus in air at 100 μ. The resultant energy densities were similar for the two instruments. Based on these results, we used similar parameters in humans, and again found that the total energy density required to make an iridotomy was approximately the same, whether using a single burst or a pulse-train.

In both monkeys and humans the ease with which an iridotomy could be made and its size varied from eye to eye with either the argon or the Nd:YAG laser. The iridotomy produced by a single burst of 18 to 20 mJ was disappointingly small and may have been due to the fact that they were placed in the second and third positions and after a 16 mJ iridotomy had already been made in the same eye (Table I). There was a great deal of pigment dispersion and iris debris in the aqueous humor at the time the 18 and 20 mJ bursts were given. It is possible that uveal material

TABLE VI: ENDOTHELIAL CELL LOSS*

	ARGON	Nd:YAG
Preoperative	2898 ± 498	2877 ± 475
One month postoperative	2585 ± 476	2771 ± 445
% Cell loss	8 ± 7%	0 ± 5%

*Mean no of cells ± standard deviation.

liberated into the aqueous can limit the effect of subsequent Nd:YAG burns in a manner similar to that experienced with the argon laser.

In both monkeys and humans a single burst of 4 or 5 mJ was insufficient to consistently produce an adequate iridotomy. These results suggest that either 5 mJ with a pulse-train of 3, or 10 mJ as a single pulse, should be employed for the first treatment, if the goal is to make a laser iridotomy with a single burn.

Although there was no significant rise in the mean IOP following either an argon laser iridotomy or a Nd:YAG laser iridotomy in humans, the response was highly variable from eye to eye. It was particularly disconcerting to note that 24% of eyes had an IOP greater than 35 mm Hg within 2 hours after treatment with either the argon or Nd:YAG laser. Although most eyes can probably sustain such a pressure rise for this period of time without visible damage to the optic nerve or visual field, some patients may have more advanced glaucoma to begin with, and may be more vulnerable to brief pressure spikes. Such patients need to be monitored and provided specific treatment for pressure control, when necessary.

Not only was there no significant difference between the pressure rise after argon laser iridotomy, compared to Nd:YAG laser iridotomy, but there was also no significant difference in the number of eyes having immediate postoperative IOP spikes of at least 10 mm Hg. Six (38%) argon-treated eyes and eight (29%) Nd:YAG-treated eyes had an IOP elevation of at least 10 mm Hg, but there was no correlation between the amount of IOP rise, the level of anterior chamber inflammation, preoperative IOP level, or iris bleeding.

SEM after Nd:YAG laser iridotomies in monkeys failed to show any evidence of permanent damage to the corneal endothelium. This was consistent with earlier studies showing that there was no permanent damage to the corneal endothelium in normal monkey eyes after argon laser iridotomy.[7] This differed from the results in our human eyes, where specular microscopy revealed an 8% decrease in central endothelial cell count in the argon-treated eyes, but no decrease following treatment with the Nd:YAG laser ($P < 0.01$).

In some cases there occurred a permanent opacity of the corneal endothelium located within the line of laser treatment. The endothelial burn after argon laser iridotomy probably resulted from direct thermal injury in these shallow-chambered eyes. The occasional focal corneal damage that could be seen after treatment with the Nd:YAG laser may well have resulted from the laser's shock wave. In two instances there occurred a large area of trauma to Descemet's membrane that resembled shattered

glass. A photograph was taken 15 minutes afterward, but it failed to record this observation (the cornea appeared normal) and the following day the cornea appeared normal by biomicroscopy.

Hyphema rarely complicates argon laser iridotomy and none developed in the human eyes treated in this series. This is due to the photocoagulation of vessels adjacent to the iridotomy. However, some bleeding occurred following Nd:YAG iridotomy in all of the animal eyes and in nine human eyes. These results are similar to those observed after treatment of monkey and human eyes with the Q-ruby laser.[3,4] One must be particularly cautious in using the Nd:YAG laser to create iridotomies in inflamed eyes with engorged iris blood vessels, or eyes with recurrent uveitis where potentially serious bleeding might occur.[8]

Lenticular opacities occurred in four monkey eyes with total energies of 4 to 30 mJ and in one eye there occurred rupture of the anterior lens capsule immediately behind an iridotomy made with 6 mJ of energy and the pulse-train of 5. It is possible that long pulse-trains are more dangerous than shorter ones or single bursts because the iridotomy may have opened in the middle of the pulse-train to allow unobstructed delivery of laser energy to the lens. If that is the case, then a single burst or a short pulse-train of 2 or 3 is to be preferred over pulse-trains of 5 or more. The potential for causing lenticular damage emphasizes the need to exercise careful judgement with regard to the amount of energy used, and to take great care to focus the laser on the iris, or just anterior to it, rather than behind it. One should also avoid the temptation to enlarge a patent iridotomy because the chance of delivering a damaging pulse directly to the lens is more liable. An added precaution requires that the iridotomy be placed in the periphery, beyond the anterior lens curvature, where the separation of iris from anterior lens capsule is greatest.

Focal lens opacities in the human eye were significantly more common behind argon iridotomies (seven eyes) than Nd:YAG iridotomies (no eyes). Admittedly, some Nd:YAG lens opacities might have been missed because of the poorer view afforded by a smaller iridotomy, and this did occur in the monkeys where two lenticular opacities were not detected until the time of gross pathological examination.

One-third of argon laser iridotomies become more than 50% closed with pigment within the first postoperative month.[3] This is usually not a serious problem and the pigment can be easily dispersed with further laser treatment. No evidence of iridotomy closure was seen in Nd:YAG-treated eyes. This is similar to our limited human experience with the Q-ruby laser.[4] The argon laser's thermal energy does not cause such loss of surrounding iris pigment epithelium, but certainly loosens it enough

that one can see plaques of pigment epithelium floating into the iridotomy, beginning immediately after treatment. This slow disruption of adjacent pigment epithelium following argon laser treatment may be more conducive to subsequent closure of the iridotomy than occurs after treatment with the Q-switched lasers where the bordering pigment epithelial cells are less stimulated to proliferate or appear less apt to break free and close the opening.

Histologic study of the monkey eyes following Nd:YAG iridotomy demonstrates that closure occurs when the pigment epithelium bridges the iridotomy and clump cells move in over the bridge. At the same time the walls of the iridotomy appear to be pulled closer together, perhaps by fibrin, to eventually close the defect, in many cases. The difference in postlaser inflammation between human and monkey eyes may explain why the Nd:YAG iridotomy in humans so seldom closes. However, regeneration of stromal cells has been demonstrated in rabbit eyes[9] and must be considered a possibility in monkey eyes, too.[10]

The Nd:YAG laser provides a means to perform an iridotomy with far fewer burns than required with the argon laser and has great potential for creating an iridotomy in eyes where the argon laser had failed. Because it requires so few applicatons, the procedure is far less tiring for subjects than when the argon laser is used and the chance for creating a permanent opening is far greater. There are certainly potential hazards, as shown in these animal studies. But if its long-term safety in humans is as good as suggested in this short-term study, then the Nd:YAG laser will become a most useful modality for the treatment of angle-closure glaucoma.

SUMMARY

In a prospective study the Nd:YAG laser was used to create iridotomies in cynomolgus monkeys, using various levels of energy and pulse-trains of 1 to 9. Although no change occurred in the endothelial cell count of the cornea, opacities of the corneal endothelium and lens did occur. In addition, one eye showed rupture of the anterior lens capsule immediately behind the iridotomy.

Most of the iridotomies in these animals closed within 3 to 4 weeks. Attenuated pigment epithelium bridged the gap within 9 days and in many sections it appeared that the iridotomies closed by fibrous contraction or early stromal regeneration.

A prospective short-term clinical study evaluated argon and Q-Nd:YAG laser iridotomies in 42 eyes of 21 patients with primary chronic angle-closure glaucoma. In each patient one eye was randomly treated with an

argon laser iridotomy and the fellow eye with a Nd:YAG laser iridotomy. In every case a patent iridotomy was created in one session. A mean of 12 ± 11 and 0.033 ± 0.025 Joules was required to complete an iridotomy with the argon and Nd:YAG lasers, respectively. Thirty percent of the argon iridotomies became sufficiently closed with pigment to require retreatment; whereas none of the Nd:YAG iridotomies closed. A postoperative rise in IOP greater than 10 mm Hg was seen in 38% argon- and 29% Nd:YAG-treated eyes. Although bleeding around the iridotomy occurred in 48% of eyes, in no case was this of significant consequence. No acute lens damage was observed in the Nd:YAG-treated human eyes, while 43% of lenses in the argon group had focal opacities. Thirty-three percent of Nd:YAG- and 24% of argon-treated eyes had focal, nonprogressive corneal opacities above the iridotomy. Specular microscopy showed a significant central corneal epithelial cell loss in argon laser eyes only. The potential of creating a laser iridotomy with a single burst of energy is extremely attractive and worthy of further investigation.

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DISCUSSION

DR MAX FORBES. Argon laser iridotomy has largely replaced surgical iridectomy in the treatment of pupillary block angle-closure glaucoma. A penetrating hole is created with the laser by thermal vaporization of iris tissue. The Abraham contact lens is indispensable for tight focus and concentration of the laser energy. In most patients conventional treatment parameters involving 0.1 to 0.2 second burns with the continuous wave argon laser result in gradual vaporization of the iris stroma followed by relatively simple disintegration or dispersion of the underlying pigment epithelium. This highly successful procedure represents a major breakthrough for ophthalmology.

Even the most successful procedures have limitations however, and argon laser iridotomy is no exception. Stromal vaporization is difficult to achieve in some light blue irides which lack sufficient pigment to absorb the laser emission, and in some dark brown irides which absorb the energy but resist thermal decomposition. With determination and persistence an adequate iridotomy can be achieved in a single session in most of these eyes. Nevertheless there remains a small subgroup in which success must await a second session several weeks later when the previously-treated stroma has become more amenable to penetration. Building on the work of prior investigators Doctor Kolker has developed special techniques to facilitate single-session hole formation in these exceptionally difficult cases.

Heat-resistant dark brown stroma is encountered mainly among black, hispanic, and oriental patients. Doctor Kolker has observed that his usual 0.1-second burns tend to coagulate this type of stroma producing a char which is even more resistant to vaporization. He has been able to avoid char formation by using multiple rapid 0.02-second burns of sufficient energy to vaporize tiny bits of stroma without generating enough heat to coagulate surrounding tissue. After gradual erosion of a stromal crater, the remaining pigment epithelium can be obliterated without difficulty.

In light blue irides with nonabsorptive stroma, virtually all of the heat must be generated by the pigment epithelium. After the pigment epithelium has been destroyed, any residual overlying stroma may be virtually impossible to penetrate. Hence, the pigment epithelium must be used to maximum advantage at the outset by an initial long duration high energy burn which transmits sufficient heat to vaporize the overlying stroma. I believe that is the essence of Doctor Kolker's strategy although he reports that the resultant gas bubble then serves to condense subsequent laser applications rendering them more effective than otherwise. I wonder if he can explain how a gas bubble could exert such an effect since it presumably has a lower index of refraction than the surrounding media. I should also like to ask Doctor Kolker if he has tried spot sizes larger than 50 μ for his initial long duration high energy burns in an attempt to increase the area of stromal vaporization. If so, what were the results?

I have enjoyed the opportunity to review this fine paper. It has the stamp of analytical and empirical authenticity. In short, Doctor Kolker's methods make good sense and they work. I expect to improve my own performance by using

them although I doubt that even these methods can uniformly produce easy single-session success in every recalcitrant case.

There is one area in which my judgment differs somewhat from that of Doctor Kolker. He advocates performing argon laser iridotomies on both eyes in one sitting in almost all patients. I realize that results will be excellent almost all of the time. However, argon laser iridotomy is not a risk-free procedure. It is often used as a prophylactic measure on eyes with excellent vision in which any untoward development would necessarily be a matter of grave concern. Under such circumstances, I believe it prudent in most cases to demonstrate an unequivocally successful outcome on the first eye before proceeding to the second eye.

I should like to congratulate Doctor Kolker for this valuable contribution and thank him for providing me with a copy of his manuscript well in advance of the meeting.

The Q-switched Nd:YAG laser was first developed by Doctor Fankhauser, who was able to produce iridotomies by means of single shots using a burst mode of four pulses with energy levels of 4 to 10 mJ/pulse. These rapid 12-nsec bursts caused explosive photodisruption of iris tissue rather than the more familiar thermal vaporization associated with the argon laser. Since such single shot iridotomies are technically feasible, one would like to know whether they are safe and reliable, as well as how they compare with argon laser iridotomies. These questions turn out to be more complex then might be expected because there are now extant a variety of Q-switched Nd:YAG lasers which, in turn, offer a variety of iridotomy parameters and strategies. In an extensive systematic experimental and clinical investigation, the authors have provided an entire foundation of reliable information about this exciting new procedure.

Two Nd:YAG lasers were used in this study, the Coherent, which can deliver a burst mode of up to 6 mJ/pulse with a 100 μ focal spot, and the American Medical Optics, which delivers a single pulse of up to 20 mJ with a 25 μ focal spot. Patent iridotomies were achieved in all 21 human eyes but more than a single shot was needed in some cases. Based on their results, the authors estimate the energy levels for a single shot iridotomy to be 10 mJ for a single pulse and 5 mJ for a pulse-train of 3. These settings appear to be safe but they may not succeed in every case. One would suspect that the thicker dark brown iris might require higher energies for penetration than the thinner light blue iris and I would like to ask Doctor Pollack if that is correct.

Anterior lens capsule rupture occurred at 1 out of 24 treatment sites in eight monkey eyes, and a burst of 5 pulses had been used at that site. Hence, the potential hazardous effect of either long bursts or multiple shots at one site must not be overlooked. In the human eyes, the authors did not place extra shots at the same location. Whenever the first shot failed to penetrate the iris the next shot was set at a higher energy level and focused at a different site in order to minimize the risk of lens capsule injury.

Comparisons between Nd:YAG laser iridotomies and argon laser iridotomies are of special interest. Whereas thermal action of the argon laser causes migration

of surrounding pigment epithelium into the defect thereby leading to delayed closure of small iridotomies (30% in this series), all 21 Nd:YAG laser iridotomies remained patent despite their relatively small size. Hence, small Nd:YAG laser holes may not need to be enlarged by additional shots which might be harmful. The corneal endothelium fared quite well after Nd:YAG laser iridotomies compared to a surprising 8% decrease in central endothelial cell count when the argon laser was used. With regard to inflammation and pressure, single shot low energy Nd:YAG laser iris photodisruption appeared to cause just as much release of debris into the anterior chamber as multiple burn higher energy argon laser iris photovaporization and the incidence of immediate pressure rise was much the same with both lasers. Small iris hemorrhages occur with the Nd:YAG laser but they do not seem to be clinically significant, at least not in noninflamed eyes with nonhyperemic irides.

I suspect that the lure of a single shot Q-switched Nd:YAG laser iridotomy will prove to be irresistible. It is for me, but I am still trying to determine the optimal parameters. I should like to ask Doctor Pollack whether he observed any relationship between focal spot size and the size of the iridotomy. In particular, did the 100 μ focal spot of the Coherent laser produce a larger hole than the 25 μ focal spot of the American Medical Optics laser? Also, does a burst mode offer any advantage over a single pulse of equivalent total energy?

Doctor Pollack has been a consistent leader in the development and promulgation of argon laser iridotomy. With this outstanding paper Doctor Pollack and co-workers have made a major contribution to the development of an even more advanced method of creating a laser iridotomy, a method which might replace the one he so diligently pioneered. I should like to thank Doctor Pollack for providing me with a copy of the paper well in advance of the meeting.

DR EVERETT J. OLENICK. In considering the difficultgy of laser iridectomy or iridotomy in patients with light blue irides and if, for example I, being blue-eyed, were to undergo such a procedure, it would be hoped that the operator might search carefully over the entire iris surface to locate a freckle or pigmented fleck that could serve as a treatment point. Since the resulting apertures seem so small as not to induce diplopia, would it not be likely that greater certainty of penetration and subsequent drainage would follow such a choice while yet reducing the problems encountered in the less responsive nonpigmented areas? It would seem that such a site selection might be more feasible even though its location might be elsewhere than superiorly.

Doctor Irvine's paper, presented earlier at this meeting, introduces another element relevant to this discussion. He reported unexpectedly low thresholds of irreversible retinal damage in experimental animals exposed to the unfiltered light of operating microscopes. The patient has always rightly been our object of primary concern, but, in the face of these studies, must we not now begin to recognize that the physician at the opposite end of the microscope could also become a potential victim?

Doctor Kolker pointed out this morning that none of the present laser instru-

ments seem to be absolutely perfect or consistent in their calibration of wavelength or light intensity. The effectiveness of their cut-off shields also appeared somewhat variable or uncertain when appraised realistically. This becomes particularly striking when we recall that only last evening Doctor Blodi, in sharing his amazing philately collection, displayed a series of postage stamps honoring ophthalmologists of the past who had become blind. There doubtlessly must be physicians here today who can remember with me the gnarled hands and scarred, disfigured features of early roentgenologists. The parallel possibility of progressive macular damage to the present and upcoming ophthalmologists who will face year after year of cumulative exposure to reflected light from the operating microscope or the partially filtered laser rays; becomes a serious prospect indeed. Additionally, while using today's binocular instruments, the maculae of both eyes are exposed to equal hazards. This entire matter should thus come under consideration as a meritorious project for intensive review and further exploration.

The cordiality of this outstanding meeting has been a delight, and I thank the Society most sincerely for the privilege of attending and participating in this discussion.

DR J. WALLACE MCMEEL. I would like to briefly comment on Doctor Kolker's question about the power of the lasers. There is a commercially available laser that does have the power reading at the far end of the optical system and when there is a discrepancy greater than 10% between the input and the output a light does go on. However, when using the laser one uses the power that produces the appropriate burn. The importance of power data is primarily to create data for a meeting such as this for a report in the literature. It is a deficiency of most lasers but it can be commercially available.

DR J. DONALD M. GASS. I want to make a comment about Doctor Pollack's paper and ask a question. It seemed to me a rather unique approach to do a laboratory experiment to determine whether the procedure might work in humans, and in spite of what appeared to be an unfavorable result in monkeys to proceed to do the procedure in humans. I would like to know how they had the guts to do that or did they, in fact, begin with the humans?

DR IRVIN P. POLLACK. I enjoyed Doctor Kolker's comments but I want to share some concerns. I also tried treating through the bubble, to see if this approach would give a better result and it often appeared to be helpful. However, I found there was a major problem in many cases, when the anterior surface of the bubble came close to the corneal endothelium. After all, these are shallow-chambered eyes and when one burns through the bubble the overlying endothelium may develop a permanent scar. Secondly, I would advise extreme caution whenever using a pulse time of 0.5 seconds. This is a long time. It extends beyond the blink reflex and, as a result, the eye frequently moves upward with the Bell's phenomenon, producing an iris char that is much larger than desired. An even greater fear

is that the eye may move in a way that allows the pupil to fall in line with the laser beam and this could be very dangerous.

I want to thank the discussants for their excellent comments and questions. I believe that the dark brown iris does require more energy to penetrate but we were unable to analyze the data for this question. There was only a total of 21 patients and we were unable to come up with a statistically valid answer. Furthermore, the responses varied greatly, so that I can't give you any ideal setting or combination of settings.

In general, we find that the best way to begin treatment is with a given power, perhaps 10 mJ. If that is unsuccessful, then we increase the power 2 mJ and move to a second site. If treatment at the first site does not completely penetrate the iris, then we feel that it is dangerous to proceed at that same site, for fear that we might end up going right through a small opening and deliver an excessive amount of energy to the anterior lens capsule.

Doctor Forbes asked if a long pulse-train was better than a single pulse. Unfortunately, we cannot answer that with certainty. It did appear that in some cases the longer pulse-train was more efficient than the single pulse. This is certainly to be expected—the total energy of a single burst with 10 mJ is far less than a pulse-train of 5 and 10 mJ. But our great fear, in retrospect, is that a longer pulse-train may open the iridotomy, let's say, at the third pulse in the series. That means that subsequent pulses might go through the iridotomy unimpeded. The monkey eye that I showed you with a broken anterior capsule was treated with a pulse-train of 5. The real question that we must ask is if pulse-trains of 5 are dangerous, should we use only pulse-trains of 3 or less to be sure that we do not pour too much energy through the iridotomy?

With regard to inflamed eyes, these are cases presenting greater danger to bleeding. We have treated eyes with recurrent uveitis with the Q-switched ruby laser and found that these eyes get much more bleeding than usual. I cannot tell you about the Q-switched Nd:YAG laser, but suspect that the chance of excessive bleeding is a threat, when treating the inflamed eye.

The next two questions regarded the relationship between spot size and iridotomy size. We used two lasers, one of which had a spot size of 100 μ in air and the second had a spot size of 25 μ. If we take into account the energy used with each instrument to make an iridotomy and compare the energy density of these two, we find no significant difference in the size of the hole. However, this was not studied in a prospective manner.

Finally, the animal studies were done first and once the safety of the instruments were established, we proceeded in two directions: first, we began a more complete study in monkey eyes and at the same time began a separate prospective study in humans. To our surprise, we found the capsular rupture in one of the animal eyes. Fortunately, we have still found no similar major complication in humans.