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Comparison of Contact and Free Beam Laser Endarterectomy[1]

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Free beam laser endarterectomy (LE) and contact laser endarterectomy (CLE) were compared in 15 arteriosclerotic New Zealand white rabbits. The rabbits underwent balloon catheter trauma to the thoracoabdominal aorta and were fed a 2% cholesterol diet for 18 weeks. Thoracoabdominal exploration was performed under general anesthesia and multiple endarterectomies were performed in each rabbit. Atheromas were dissected from arteries with laser radiation and end points were welded in place with laser radiation. LEs (N = 8) were performed with argon ion radiation delivered through a 400 μm fiberoptic. Power was kept constant at 1 W and the average fluence was 97.5 ± 6.6 J/cm^2. CLEs were performed with conical sapphire probes powered by either argon ion radiation (N = 12) or Nd–YAG radiation (N = 10). Power used was 1 W to 4 W for each laser. Average argon ion fluence was 117.8 ± 3.1 J/cm^2 and average Nd–YAG fluence was 611.1 ± 34.4 J/cm^2. Following the operations, aortas were removed, fixed, serially sectioned, and stained. Microscopic study revealed welded end points with LE but not with CLE. There were no perforations with LE. There were 11/12 perforations with argon ion CLE and 8/10 perforations with Nd–YAG CLE. Free beam laser endarterectomy is superior to contact laser endarterectomy for experimental atheromas.

Laser endarterectomy has been described as an open surgical procedure for laser removal of atherosclerotic plaques [1–3]. Several lasers have been evaluated for this operation. These lasers (argon ion, neodymium–YAG, and carbon dioxide) require familiarity with free beam laser surgery. This eliminates tactile feedback which is an important sensation to many surgeons. Sapphire crystal probes have been used for contact laser surgery as well as for laser angioplasty [4–8]. The theoretical advantages of these probes are that they allow precise localization of laser radiation as well as tactile feedback to the operating surgeon. In an effort to restore tactile sensation to the laser endarterectomy operation, we have studied conical sapphire crystal laser knives for the removal of atheromas in arteriosclerotic rabbits. This report describes the use of argon ion and Nd–YAG laser radiation delivered through sapphire crystal laser knives for the performance of laser endarterectomy.

MATERIALS AND METHODS

All experiments were performed with the New Zealand white rabbit arteriosclerosis model. They received humane care in compliance with the Animal Care Committee of the University of California, Irvine, and the *Principles of Laboratory Animal Care* formulated by the National Society for Medical Research and the *Guide for the Care and Use of Laboratory Animals* (NIH Publication No. 80-23, revised 1978). Under general anesthesia (intramuscular acepromazine 0.5 mg/kg, xylazine 30 mg/kg, and ketamine 50 mg/kg), 16 rabbits had the right common femoral artery exposed and a No. 4 Fogarty catheter was advanced into the thoracoabdominal aorta to denude the endothelium. After recovery from anesthesia, the animals were begun on a 2% cholesterol diet, which was continued for 16–20 weeks. This protocol has been shown to produce significant arteriosclerosis in 86% of rabbits [9].

Arteriosclerotic rabbits were anesthetized (intramuscular acepromazine 0.5 mg/kg, xylazine 3 mg/kg, and ketamine 50 mg/kg) intubated, and ventilated with a small animal respirator (Ohio V5A) with oxygen and halothane (Ohmeda VMC anesthesia machine). Oxygen saturation was constantly monitored through an infrared sensor (Ohmeda 5120 oxygen monitor). Supplemental ketamine (50 mg/kg intravenously) was administered during the procedure to maintain anesthesia. A thoracoabdominal incision was made to expose the aorta. Heparin (3.0 mg/kg intravenously) was administered and proximal and distal vascular control was obtained. A longitudinal ar-

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teriotomy exposed the diseased segments of the thoracic and abdominal aorta. Open laser endarterectomy was performed. A line of laser craters was created with individual laser exposures proximal and distal to an atheroma. The lines were connected by constant laser application to create proximal and distal end points. The atheromas were grasped with forceps and constant laser delivery was used to develop a cleavage plane just beneath the internal elastic lamina in order to dissect the atheromas from the aorta. Constant laser exposure was used to weld the end points in order to provide a secure transition from endarterectomy surface to intima. All surgery was performed using optical magnification (3.5 to 4.5 loupes). In Group I (five rabbits), free beam laser endarterectomy was performed with an argon ion laser with mixed wavelengths, 488 and 514.5 nm (Model 880, Cooper Inc., Palo Alto, CA). Laser radiation was directed through a 400 μm quartz fiber at 1.0 W to produce a laser spot approximately 0.5 mm diameter. The optical fibers were freshly cut for each experiment. Power delivered was measured directly from the laser head and the delivery was verified at the beginning and conclusion of each experiment with a power meter (Model 210, Coherent, Inc., Palo Alto, CA). The delivery of energy was regulated by the duration of exposure and this ranged from 1.0 to 30 sec. At 1.0 W power, this corresponds to 1.0 to 30 J per exposure.

In Group II (five rabbits), endarterectomy was performed with argon ion laser radiation delivered through a 400 μm quartz fiber to artificial crystal sapphire tips (SLT Inc., Malvern, PA). The artificial crystal sapphire tips are made of Al_2O_3 and they have a conical shape with a rounded tip of 0.2, 0.4, 0.6, or 0.8 mm diameter. The tips are positioned in contact with the laser fiber through a specially designed handpiece (Fig. 1). The spot size delivered is 0.5 to 1.0 mm diameter. The contact laser endarterectomies were performed with the power 1.0 to 4.0 W (measured directly at the laser head). The energy delivered was regulated by the duration of laser contact and this ranged from 1.0 to 30 sec.

In Group III (six rabbits), endarterectomy was performed with Nd–YAG laser radiation (Model 8000-3, Molectron Medical, Santa Clara, CA) delivered through a 600 μm quartz fiber to an artificial sapphire tip (SLT Inc., Malvern, PA) 0.2, 0.4, 0.6, or 0.8 mm in diameter. The tips were positioned in contact with the optical fiber through a specially designed handpiece. The spot size delivered to atheromas ranged from 0.5 to 1.0 mm diameter. Contact laser endarterectomies were performed with

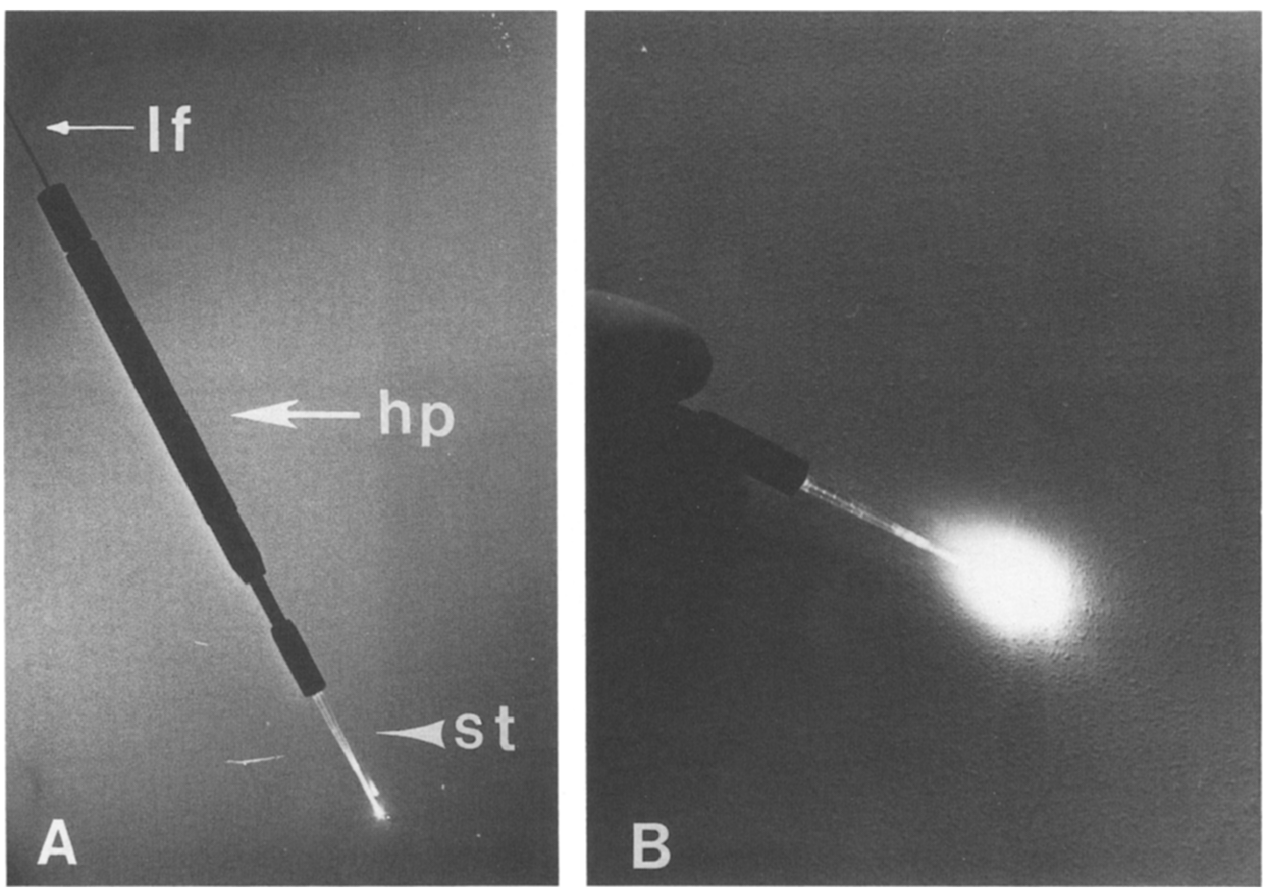

FIG. 1. Sapphire knife (A) complete assembly showing fiberoptic cable (lf) inserting into the handpiece (hp) which secures the sapphire crystal (st). (B) sapphire knife illuminated by an argon ion laser beam.

power 1.0 to 4.0 W which was measured directly from the laser head. Total energy delivered was determined by the duration of laser contact which ranged from 1.0 to 30 sec.

Following laser endarterectomy, aortas were removed from the rabbits and the rabbits were sacrificed (barbiturate injection). The aortas were rinsed in Ringer's lactate solution. They were separated into surface and end point specimens and the specimens were pinned on Teflon blocks. The specimens were fixed in 3% glutaraldehyde in phosphate buffer at 4°C for 24 hr, rinsed in phosphate buffer, dehydrated through an alcohol series, removed from the Teflon, and embedded in paraffin. Serial sectioning was performed at 6 μm intervals and the final slides were stained with hematoxylin and eosin.

Gross and light microscopic findings were used to grade the surfaces and end points. Scores of 1 to 4 were assigned to each specimen. For the surface, 1 = perforation, 2 = wrong cleavage plane, 3 = rough surface, and 4 = smooth surface. For the end points, 1 = perforation, 2 = intimal flap, 3 = rough transition, and 4 = smooth transition. The specimens were examined independently by two of the authors and the results were averaged to determine the final score for each specimen. The scores for Groups I, II, and III were compared by the Kruskal-Wallis test with tied midranks and verified by the Wilcoxon test [10]. Differences amounting to $P < 0.05$ were considered significant.

RESULTS

There were 8 endarterectomies performed in Group I (free beam argon ion laser), 12 endarterectomies performed in Group II (contact argon ion laser), and 10 endarterectomies performed in Group III (contact neodymium–YAG laser).

By gross inspection, the free beam argon ion laser endarterectomies were satisfactory. The surfaces were clean. There was no residual atheroma and the end points were fused. There were no perforations seen and there was no evidence of thermal damage to the aorta or to surrounding structures. By light microscopic inspection, the surfaces were seen to be just beneath the internal elastic lamina in all the experiments (Fig. 2C). The end points were securely fused by laser radiation with an even transition from endarterectomy surface to intima (Fig. 3). The mean (±SEM) fluence used to perform free beam argon ion laser endarterectomy was 97.5 ± 6.6 J/cm^2.

The gross appearance of contact argon ion laser endarterectomies (Group II) was different from the gross appearance of Group I endarterectomies. The surfaces appeared clean and free of debris but the end points were ragged with uneven edges and there was evidence of thermal injury at the end points manifested by charring and discoloration. Microscopically, the surfaces were evenly dissected (Fig. 2A), but there were perforations seen along the surfaces in 5/12 experiments and at the end points in 10/12 experiments (Fig. 4A). The perforations were seen along the surface or at the end points in all but 1 of the experiments and the end points were not welded in place (Figs. 4B and C). The mean fluence used to perform contact argon ion laser endarterectomies was 117.8 ± 3.1 J/cm^2.

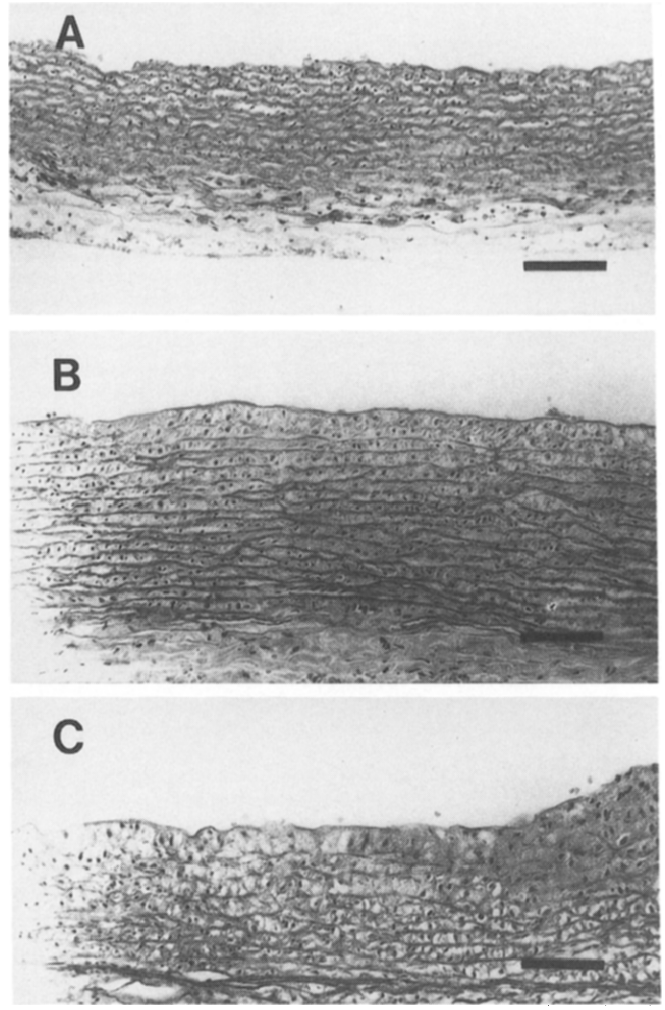

FIG. 2. Endarterectomy surfaces following open laser endarterectomy. (A) contact argon ion surface is smooth and the cleavage plane has been developed just beneath the internal elastic lamina. (B) Contact Nd–YAG surface is also smooth with the cleavage plane at the innermost fibers of the media and normal architecture of the remaining arterial wall. (C) Free beam argon ion surface is smooth and even. There is no evidence of thermal injury and the media retains its normal configuration. Calibration bar = 100 μm (hematoxylin and eosin).

The gross appearance of contact neodymium–YAG laser endarterectomies (Group III) also showed clean endarterectomy surfaces but uneven, ragged end points with thermal discoloration. Microscopic examination showed cleanly dissected surfaces (Fig. 2B), but there were perforations along the surface in 5/10 experiments and at the end points in 8/10 experiments (Fig. 5A). The end points were welded in place in only one experiment and this one exhibited an uneven transition (Fig. 5B). The mean fluence used to perform contact Nd-YAG laser endarterectomies was 611.1 ± 34.4 J/cm^2.

The mean endarterectomy surface score was 3.5 for Group I, 2.58 for Group II ($P < 0.005$ compared to Group I), and 2.0 for Group III ($P < 0.001$ compared to Group I). The mean endarterectomy end point score was 3.75 for Group I, 1.2 for Group II ($P < 0.001$ compared to Group I), and 1.3 for Group III ($P < 0.001$ compared to Group 1). The results are summarized in Tables 1–3.

DISCUSSION

Endarterectomy is one of the fundamental arterial reconstructive techniques. Laser endarterectomy was developed to utilize the unique properties of laser radiation during operative vascular reconstruction. Prior studies have shown that laser endarterectomy can be performed with a free laser beam to dissect plaques from an arteriosclerotic artery and weld the end points. The best experimental results have been obtained with the free beam from an argon ion laser at power 1.0 W. This technique has proven useful in early clinical trials for peripheral vascular endarterectomy [11], and carotid endarterectomy [12]. In both the laboratory and the operating room, smooth endarterectomy surfaces with welded end points have been produced. The free beam operation requires dissecting with a "no-touch" technique, however, so that tactile feedback, which can give important information about the tissues, is eliminated.

Contact laser surgery (using neodymium–YAG laser light) has been proposed by Joffe and associates for several surgical applications including dissection, hemostasis, and solid organ resection [4–6]. The theoretical advantages include direct laser radiation–target tissue interaction with tactile feedback and no backscattering of laser light. The probes are also reported to reduce the depth of laser-induced tissue damage and to reduce the laser power required for dissection because of their efficiency over a free laser beam. Contact probes have also been developed for use with catheter delivery systems for laser angioplasty and in this setting, the probes have been shown to produce more reliable and more easily controlled atheroma ablation than a free laser beam or a laser beam delivered

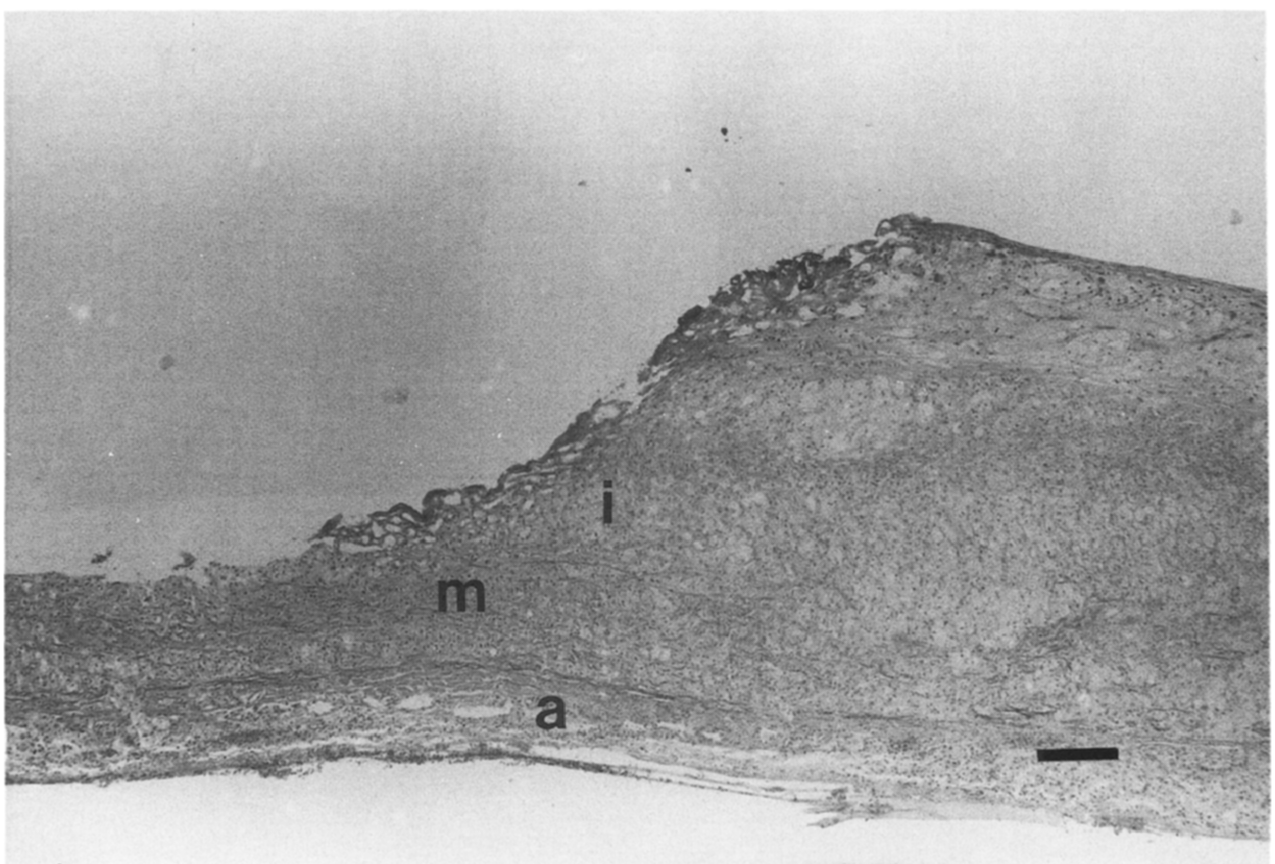

FIG. 3. Distal end point following free beam argon ion laser endarterectomy. There is a tapered transition from intima to endarterectomy surface. The arterial layers are fused and there are mild thermal changes (carbonization and lacunae) in the outermost layers. i, Intima; m, media; and a, adventitia. Calibration bar = 200 μm (hematoxylin and eosin).

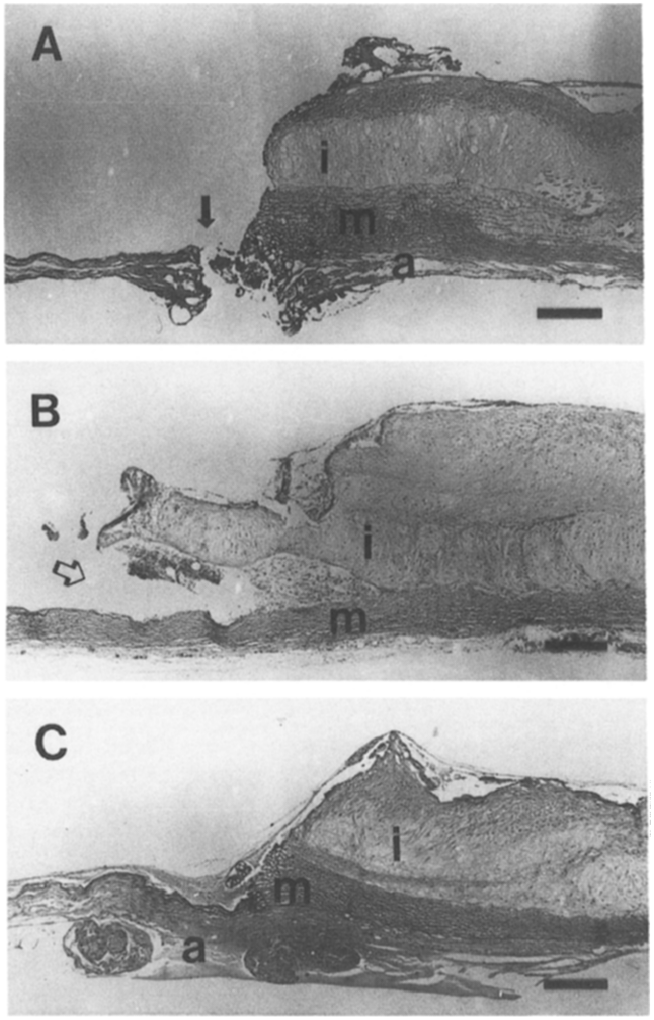

FIG. 4. Distal end points created by contact argon ion laser endarterectomy. (A) Free perforation (closed arrow) is seen at the transition from surface to end point. (B) Intimal flap (open arrow) is seen between the intima and the media. (C) Full thickness injury (perforation) is seen at the transition from surface to end point. i, Intima; m, media; and a, adventitia. Calibration bar = 250 μm (hematoxylin and eosin).

through a lensed catheter [7, 8]. In the present study, both argon ion and Nd–YAG laser radiation were delivered through conical sapphire crystal knives to perform laser endarterectomy. The argon ion laser was used because laser endarterectomy can best be performed with this laser. The Nd–YAG laser was used because it is the standard power source for contact laser surgery. Both lasers are routinely available and they have fiber optic delivery systems which enable them to couple to the handpiece of the sapphire knives. The power required for surgery depends on the size of the knife—2 W for the smaller knife (0.2 mm tip) up to 4 W for the largest knife (0.8 mm tip), irrespective of the laser source. Earlier studies have shown that the optimum power output for free beam argon ion laser endarterectomy is 1.0 W [1–3] and for free beam Nd–YAG laser endarterectomy is 10 to 20 W [3, 13]. The sapphire knives actually increased power requirements for the argon ion laser but did reduce the power requirements for the Nd–YAG laser in agreement with the reports of other investigators [4, 6, 8].

The contact laser endarterectomy operations were easy to perform, but microscopic study revealed unsatisfactory results. Perforations were seen in most of the specimens and the end points were not welded. During dissection, the probes adhered to the atheromas, causing tearing and shredding of the arterial layers. This left flaps along the surface and at the end points. Tissue adherence has been reported by Peyman and associates during experimental partial nephrectomy [14]. Daikuzono and Joffe, on the other hand, reported no tissue adhesion because of the

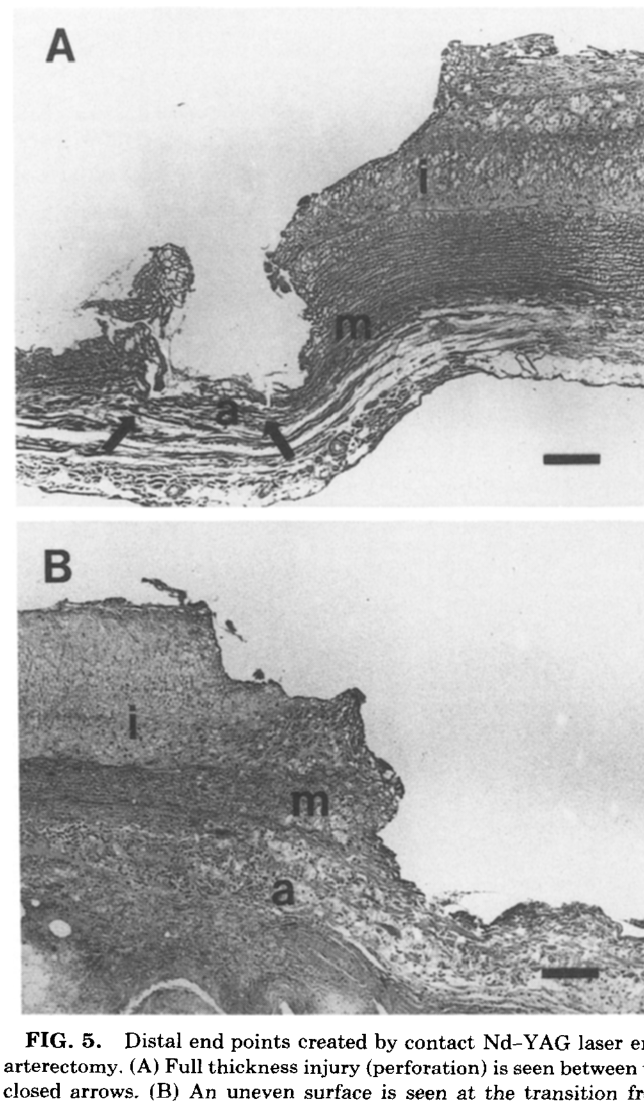

FIG. 5. Distal end points created by contact Nd-YAG laser endarterectomy. (A) Full thickness injury (perforation) is seen between the closed arrows. (B) An uneven surface is seen at the transition from endarterectomy surface back to intima. The rough surface is due to tissue adherence to the sapphire knife. i, Intima; m, media; and a, adventitia. Calibration bar = 150 μm (hematoxylin and eosin).

TABLE 1

Free Beam Argon Ion Laser Endarterectomy

Experiment number	Atheroma	Power (W)	Fluence (J/cm²)	Surface score	End points score
1	Moderate–severe	1.0	70	4	4
2	Moderate–severe	1.0	57	3	4
3	Mild–moderate	1.0	197	4	4
4	Severe	1.0	67.2	4	4
5	Moderate	1.0	70	4	4
6	Moderate–severe	1.0	71	3	3
7	Moderate–severe	1.0	81	3	3
8	Moderate	1.0	167	3	4

TABLE 3

Contact Neodymium–YAG Laser Endarterectomy

Experiment number	Atheroma	Tip (mm)	Power (W)	Fluence (J/cm²)	Surface score	End points score
1	Moderate	0.6	3	366.5	2	2
2	Moderate	0.8	4	379.5	1	1
3	Moderate–severe	0.6	3	1381.9	1	1
4	Moderate	0.8	4	786.2	3	1
5	Mild–moderate	0.4	2.9	281.3	1	1
6	Moderate	0.2	3	558.8	1	1
7	Moderate	0.4	3	424	4	3
8	Moderate	0.6	2.5	342.4	2	1
9	Moderate–severe	0.2	1–2	937.5	1	1
10	Moderate	0.2	2	652	4	1

high temperature at the tip of the sapphire knife [4]. Kim and associates [15] reported substantial thermal injury from contact argon ion laser endarterectomy, but no tissue adherence. In the present study, the high temperature at the tip resulted in thermal injury to the arteries, but did not prevent tissue adherence. The high temperature could also have been responsible for the nonwelded end points because tissue fusion reportedly takes place at lower temperatures than tissue ablation [16]. The free beam argon ion laser endarterectomies left smooth endarterectomy surfaces with welded end points. The depth of plaque penetration by the argon ion beam was consistent and easily controllable. There were no thermal injuries and no perforations.

TABLE 2

Contact Argon Ion Laser Endarterectomy

Experiment number	Atheroma	Tip (mm)	Power (W)	Fluence (J/cm²)	Surface score	End points score
1	Moderate	0.6	4	52.8	4	1
2	Moderate–severe	0.6	3	164.73	4	1
3	Moderate–severe	0.6	2.5	170.6	4	1
4	Moderate	0.8	2.5	144.3	1	2
5	Moderate	0.8	3.0	172.7	1	1
6	Moderate	0.4	2.5	93.53	1	1
7	Moderate	0.2	2.5	116.4	2	1
8	Moderate	0.4	2.5	105.2	4	2
9	Moderate	0.6	2.5	113.28	4	1
10	Moderate	0.2	1–2	97.8	1	1
11	Moderate	0.2	3.0	84.27	1	1
12	Moderate	0.2	3.0	98.0	4	1

The rabbit arteriosclerosis model has proven to be extremely reliable in predicting the response of human arteries to laser endarterectomy even though rabbit arteriosclerosis is not as severe as human arteriosclerosis. The rabbit atheromas are uniform throughout the traumatized aorta, with a thickened and discolored intima. Individual atheromas have fibrous caps overlying areas of inflammation, fatty infiltration, and microcalcification, which often involves the internal elastic lamina and the superficial layers of the media. In the rabbit model, consistently good results have been obtained using free beam argon ion laser radiation at power 1.0 W. In the clinical setting, arteries of all sizes in the peripheral vascular circulation have had successful laser endarterectomies performed using free beam argon ion laser radiation at power 1.0 W [11, 12]. We feel, therefore, that the results of the present study are highly predictive of the clinical response of human arteries to laser endarterectomy. The significant differences between contact and free beam laser endarterectomy seen in this study cause us to continue to recommend free beam argon ion laser radiation for laser endarterectomy.

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