Nonsuture microvascular anastomosis using an Nd-YAG laser and a water-soluble polyvinyl alcohol splint

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Anastomosis of rat common carotid artery was performed without sutures, using a neodymium (Nd)-YAG laser at 20 W for 100 msec; this power and exposure had been found optimal in preliminary experiments. An intraluminal intervascular splint made of water-soluble polyvinyl alcohol, which dissolved and disappeared within a few minutes after recirculation of blood, was used for precise “intima-to-intima” coaptation. No stay sutures or glue were required during the procedure.

There was a 92% patency rate 24 hours after surgery, and the anastomosed vessels were still patent on the 7th and 30th postoperative days. Complications such as aneurysm formation or stenotic change were negligible. The fusion of the muscle layer and collagen fibers of the media in the anastomosis was confirmed histologically. A tensile strength test immediately following operation and 1 week later showed that this anastomosis was significantly better than that achieved with the usual manual suture method. The major advantages of this technique, combined with use of a water-soluble polyvinyl alcohol splint, are rapidity, consistency of results, and firm fusion with no residual foreign body.

KEY WORDS • anastomosis • Nd-YAG laser • cerebral ischemia • revascularization • rat

MICROVASCULAR anastomosis is often used in neurosurgery for the repair of small vessels 1 mm or less in diameter, such as for extra-cranial-intracranial bypass operations.11,12,16 The conventional suture method, however, is time-consuming and may traumatize the vessel. Although several nonsuture methods of anastomosis of small vessels have been tried, they still present problems of reliability, consistency of results, and safety.26,17 As a possible improvement on these methods, we conducted an experimental study of microvascular anastomosis using a neodymium (Nd)-YAG laser beam with an intraluminal intervascular splint made of water-soluble polyvinyl alcohol.

Preliminary Study

The Nd-YAG laser is commonly used in tumor removal or for hemostasis during endoscopy.1,10 When it is applied in vascular anastomosis, the power and exposure times may be varied. In order to determine the optimal conditions for laser anastomosis, the following experiments were performed. The Nd-YAG laser apparatus has a wavelength of 1.06 μm, power ranging from 10 to 80 W, and an exposure time varying from 10 to 990 msec. The diameter of the beam through the flexible quartz fiber is 0.2 mm.

Sixty-one rats were used for the preliminary experiments. A 2-cm section of common carotid artery (CCA) was dissected out, unilaterally in 20 and bilaterally in 41, giving a total of 102 CCA specimens. The wall of each artery was cut transversely with one to three slits, for a total of 228 slits, each about 0.5 mm in length. The laser beam was projected onto the slits, and the effects were investigated. At first, the power was altered from 10 to 60 W in 10-W increments and the duration of exposure was increased from 10 to 200, ...., 900, and 990 msec in 11 steps. The irradiated artery was stained with hematoxylin and eosin (H & E) and examined photomicroscopically. The specimens receiving 10 W for 990 msec showed no change except in the adventitia. When the power was more than 40 W, the entire vessel wall underwent carbonization and/or vaporization at a 100-msec exposure, but no effect on the vessel wall resulted from a 10-msec exposure.

Based on these results, fusion of rat CCA was attempted with two low-power trials (20 and 30 W) at three exposures (100, 150, and 200 msec). With 20 W
FIG. 1. Water-soluble intraluminal intervascular polyvinyl alcohol splint. Upper: View of the actual model (inner diameter 0.4 to 0.5 mm, outer diameter 0.8 to 1.0 mm, length 7 to 10 mm). x 2. Lower: Diagram of the two-layer structure.

FIG. 2. Anastomosis procedure. Upper: Exact coapta-
tion of the cut ends (arrows) is seen. No stay sutures or glue are required. Center: The Nd-YAG laser beam is projected onto the anastomosis (beam diameter 0.2 mm, energy 20 W for 100 msec). Lower: A few minutes after recirculation, the rat common carotid artery appears to be patent. Arrows indicate the anastomosis. The polyvinyl alcohol splint has already dissolved and disappeared.

Material and Methods

Polyvinyl Alcohol Splint

Polyvinyl alcohol is made by saponifying polyvinyl acetate, and the hardness and solubility can be readily changed by adjusting the degree of polymerization and the saponification value. The intraluminal intervascular splint* used in the present study is composed of two layers (Fig. 1). The inner layer, which is exposed to blood when the circulation is reestablished, consists of a soft and rapidly soluble polyvinyl alcohol (degree of polymerization 120, saponification value 82%). The outer layer, which is in contact with the internal vessel wall after insertion, is made of a harder and less soluble polyvinyl alcohol (degree of polymerization 550, saponification value 88%).

Method of Anastomosis

Thirty-six Wistar rats, each weighing about 300 gm, were anesthetized by intraperitoneal pentobarbital, 6.5 mg/100 gm body weight. The experimental animal was fixed in the supine position and a midline skin incision was made in the neck. Using the operating microscope, the CCA (diameter of 0.8 to 1.0 mm) was exposed on one side for about 1.5 cm. Two clips were applied, the distance apart being freely adjustable; the vessel was then divided between them. Initially, the cut ends were separated by a few millimeters because of contraction, but they were approximated by adjusting the clips so that the proximal and distal ends finally overlapped about 2 mm. Fluid, saline solution, and blood were removed from around the vessel, and an intraluminal intervascular splint of water-soluble polyvinyl alcohol, with both ends cut at an acute angle, was inserted into the vessel lumen. The intima of both the proximal and the distal ends were then apposed (Fig. 2 upper). An Nd-YAG laser beam, 0.2 mm in diameter, of 20 W was applied for 100 msec to the entire circumference using an average of 49 ± 15 exposures (Fig. 2 center). No stay sutures or glue were required, and the vessel was cooled by physiological saline solution. The distal and then the proximal clip were carefully released while the anastomosis was checked for patency and leakage of blood. If leakage occurred, the clips were reapplied and laser exposure repeated until this complication was resolved. After the clips were removed, the polyvinyl

for 100 msec, there was fusion of the vessel wall without any damage to the intima; however, 20 W for 150 msec and 20 W for 200 msec caused partial carbonization of the anastomotic site. With 30 W for exposures of 100, 150, and 200 msec, a more diffuse and severe carbonization was observed, together with some vaporization. We therefore concluded that the optimal energy for Nd- YAG laser vascular anastomosis was 20 W for a period of 100 msec.

* The splint was made by and can be obtained from Prof. Yoshito Ikada, Research Center for Medical Polymers and Biomaterials, Kyoto University, Kyoto, Japan.

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alcohol splint quickly dissolved within 2 to 3 minutes on exposure to the blood, and the circulation completely recovered (Fig. 2 lower).

Results

Patency of the Anastomosis

The patency of the anastomosed vessel was examined at three postoperative intervals as follows: 1) in all 36 animals at 24 hours after anastomosis, when occlusion or separation of the anastomotic site is most likely; 2) in one-third of the animals (12 rats) at 1 week after operation, when stenosis or aneurysm formation may be found; and 3) in four of these 12 animals at 1 month later to study the long-term effects.

Results of patency testing are shown in Table 1. In 33 (92%) of the 36 rats, the vessel was patent 24 hours postoperatively and there were no abnormal findings. Immediately after the procedure, two of the three rats with unsuccessful operations showed separation of the anastomosis due to inadequate laser exposure and slow cooling without the saline solution. In the third animal, nonpatency was thought to be due to excessive laser exposure leading to occlusion. All three unsuccessful anastomoses were performed early in the series. Twelve of the 33 rats that showed good patency at 24 hours were reexamined 1 week later, and all showed complete patency with no stenosis or aneurysm formation. One month later patency was examined and found unchanged in four of these 12 animals. At that stage it was difficult to identify the anastomosis under the operating microscope.

Histological Examination

Histological specimens of the arteries, stained with H & E, were examined immediately after laser anastomosis. The muscle layer of the media and the surrounding collagen fibers had already fused, although a slight derangement of the nuclei of the muscle cell in the media was observed (Fig. 3). This suggests that there is transient damage to the muscle layer before fusion of the incised ends. The intima showed little effect; the endothelial cells were unchanged and necrotic foci were uncommon, although part of the anastomosis appeared slightly edematous and a little swollen. The elastic fibers of the vessel wall showed satisfactory fusion on elastica Van Gieson staining. One week after anastomosis, fusion in the H & E specimens seemed to be complete. These samples demonstrated a perfect healing process with minimal tissue reaction, such as cell infiltration.

Tensile Strength Test

To determine the firmness of the fusion, tension was applied to the anastomosed vessels; the results were compared with those in rat CCA anastomoses secured with 12 sutures of 10-0 monofilament nylon (Table 2). For these studies, the anastomosis was dissected out in 2-cm segments of vessel, which were fitted to a tension-

<table>
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<tr>
<th>Test Finding</th>
<th>Rats Tested</th>
<th>Patent Anastomoses</th>
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<tbody>
<tr>
<td>patent at 24 hrs</td>
<td>36</td>
<td>33</td>
</tr>
<tr>
<td>patent at 1 wk</td>
<td>12</td>
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<td>patent at 1 mo</td>
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* N = number of anastomosed vessel segments tested. Suture tensile strength is expressed as the mean ± standard deviation.
measuring device. The vessel was stretched longitudinally, and the tension at which the anastomosis separated was measured.

In the control group of five rats with sutured anastomosis the mean tensile strength measured soon after the anastomosis was 72 ± 11 gm, but in the laser-treated group of three rats the mean tension was greater than 110 gm. A comparison made 1 week later showed an anastomosis tensile strength of 90 ± 8 gm in a different control group of five rats with sutured anastomosis, while in the laser group the mean tension was still over 110 gm. This confirmed that the tensile strength at any postoperative time was significantly greater in the laser group than in the control group. It was also observed that comparatively firm fusion occurred immediately after laser anastomosis, which contrasted with the gradual increase in tensile strength of the control group.

Discussion

Although the value of revascularization procedures in the cerebral circulation is uncertain, microvascular anastomosis has been used to treat ischemic stroke, giant aneurysm, and tumors of the skull base involving tributaries of the internal carotid artery. Yonekawa and Yaşargil reported that microvascular anastomosis was essential in the transplantation of the greater omentum for brain ischemia.

Manual suture methods are difficult to use, especially in relatively inaccessible locations, and several investigators have explored the possibility of nonsuture anastomosis. For this procedure, a splint is required to approximate the intima of the incised vessels. Because none of these devices has been entirely satisfactory, we have developed and tested in vivo an intraluminal intervascular splint made of water-soluble polyvinyl alcohol. The splint was unchanged during the initial 1 to 2 minutes after insertion, but within 2 to 3 minutes after the circulation was reestablished, it had dissolved and disappeared. No fragments were observed, and it is unlikely that it caused any toxic reaction or complication such as embolism. Thus, this splint may satisfy the conditions for clinical use, as it can be closely applied to the cut ends, prevents the collapse of the vascular lumen, and enables the laser beam to be projected accurately.

Other nonsuture microvascular procedures have been found as useful as manual suture procedures, but have only been applied to vessels 3 mm in diameter or larger and could not be used for vessels of 1 mm diameter. Yamagata reported the successful use of a soluble splint combined with cyanoacrylate as an adhesive to anastomose rat CCA; however, there is concern about the possible toxicity of cyanoacrylate remaining at the operative site. During the follow-up period, problems were encountered with infection, impairment of pulsation, and dilatation of the artery.

Both CO₂ and Nd-YAG lasers have been frequently used in neurosurgery, principally for the removal of tumors because they are high-energy sources. A low-energy laser source is now available for hemostasis and repair of blood vessels.

The temperature of the vessel wall at the time of laser exposure has been measured as 74.7°± 12.6°C. This, together with the histological findings, suggested that the mechanism of fusion may be explained as follows: there is a transient and reversible dissolution of tissue protein (such as muscle fiber, collagen, and elastin) due mainly to a thermal effect immediately adjacent to the vessel ends. Prompt and firm fusion of the tissue protein follows as the temperature around the anastomosis is lowered by cooling with physiological saline solution.

The CO₂ laser also required the use of stay sutures for vascular anastomosis, which limits its use to more accessible areas. It has been suggested that, since the CO₂ laser has a longer wavelength and is less penetrating, it may not completely weld the vessel wall. Some investigators have postulated that, since the Nd-YAG laser has a shorter wavelength and deeper penetration, it may damage the intima. However, we believe that optimal beam conditions for the Nd-YAG laser can be determined and that it gives a stronger weld.

Our experiments indicate that there may be important advantages in using the Nd-YAG laser beam combined with a polyvinyl alcohol splint. The anastomosis takes only 2 to 3 minutes to perform, with minimal interruption of the blood supply. However, on some occasions, because of the inaccessibility of the lesion, it was impossible to rotate the artery and apply the Nd-YAG laser to the total circumference. Histology and tensile strength test studies confirm that the anastomosis is sound and, as no sutures are needed, the intima is undamaged. There is no residual foreign body because the polyvinyl alcohol splint dissolves rapidly and completely and is removed in the circulation. Tissue toxicity or infection does not occur since no adhesive is used and earlier wound healing may be expected because tissue regeneration is promoted.

This technique has practical advantages because the beam is only 0.2 mm in diameter and can be focused accurately through a flexible quartz fiber. It is permeable and not easily absorbed in water so that it can be applied to operative fields containing cerebrospinal fluid. We therefore conclude that the Nd-YAG laser combined with the polyvinyl alcohol splint may be valuable in microvascular neurosurgery.

Acknowledgments

The authors are indebted to Prof. Yoshito Ikada, Ph.D., Research Center for Medical Polymers and Biomaterials, Kyoto University, Kyoto, for the manufacture of the polyvinyl alcohol splint used in this study. We also thank Siber Kikai K.K., Tokyo, for kindly supplying the Nd-YAG laser.

References

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