Effects of Nd:YAG and CO₂ lasers on cerebral microvasculature

Study in normal rabbit brain

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The effect of Nd:YAG and CO₂ laser beams on cerebral microvasculature was examined in experimental animals. Soft x-ray microangiography and histological examination of the brain after Nd:YAG laser exposure revealed broad avascular or oligovascular zones in the irradiated and the surrounding edematous tissue, in which the surviving vessels were narrowed and tapered without significant leakage of blood. After CO₂ laser exposure, a wedge-shaped tissue defect surrounded by layers of charring, coagulation, and edema was observed. The main finding in the surrounding coagulation and edematous layers was dilatation of the vessels. Hemorrhage was sometimes observed, mainly in the edematous layer. These findings seem to explain the effective hemostatic capability of the Nd:YAG laser and the occasional hemorrhage following CO₂ laser exposure, especially at high energy output.

KEY WORDS • Nd:YAG laser • CO₂ laser • microangiography • hemostasis • hemorrhage • cortical lesion • rabbit • cerebrum • laser

SINCE the laser was introduced as a neurosurgical instrument in 1965 by Rosomoff and Carroll its significance and usefulness have been widely recognized. The laser has a high potentiality to perform precise and safe operations. However, several questions have arisen from clinical application of the system, one of which concerns the mechanism of laser-beam hemostasis. Currently, two different types of laser, the CO₂ and neodymium YAG (Nd:YAG) lasers, are commonly used in neurosurgery. It is well accepted that the CO₂ laser is suitable for cutting and dissection, and the Nd:YAG laser for coagulation and hemostasis. These properties have been investigated and demonstrated by several experimental and clinical studies. However, the angiographic change in cerebral microvasculature induced by exposure to these different types of laser beams has not been clearly demonstrated. Recently, we reported that post-exposure hemorrhage was frequently found with an increase in CO₂ laser power, and that such hemorrhage was rare with Nd:YAG laser exposure. The purpose of this study is to investigate the effects of these different behaviors on the cerebral microvasculature induced by the two different types of laser beams.

Materials and Methods

A laser system* which can deliver pulse waveform CO₂ and Nd:YAG laser beams separately or simultaneously was used in this investigation. The output of the CO₂ laser ranged from 0 to 20 W and that of the Nd:YAG laser from 0 to 50 W. The minimum spot size of the CO₂ laser beam was 0.7 mm in diameter and that of the Nd:YAG beam 1.2 mm. Therefore, median-power density of the CO₂ and Nd:YAG lasers was 2599 and 2211 W/sq cm, respectively. The dominant transverse electromagnetic mode (TEM) for the CO₂ laser beam was TEM₀₀ (single) and that of the Nd:YAG beam TEM₁₀ (multiple). Both laser beams were delivered through an articulated arm to micromanipulators which were coupled to a Zeiss OPMI-1 operative microscope† with a 300-mm focal length objective lens.

Twenty female Japanese White rabbits, weighing 2.5 to 3.0 kg each, were used in this study. The animals were anesthetized with pentobarbital (30 mg/kg), and

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* Laser, Model 130 YZ, manufactured by Nihon Infrared Industries Corp., Ltd., Tokyo, Japan.
† Zeiss operative microscope, Model OPMI-1, manufactured by Carl Zeiss, Inc., Oberkochen, West Germany.
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bilateral parieto-occipital craniotomies were performed. The dura was opened and the cortex on both sides was exposed. A Nd:YAG laser beam of 20 or 40 W for 2 seconds or a CO₂ laser beam of 4 or 8 W for 2 seconds was directed perpendicularly at the cortex. Immediately after the exposure, Evans blue dye (2 cc/kg in a 2% saline solution) was injected intravenously as a tracer to detect any blood-brain barrier disruption in regard to serum protein. The bone defect was sealed with a paraffin plate.

Thirty minutes after exposure, each animal was sacrificed with an overdose of pentobarbital, and the common carotid arteries on both sides were exposed. The artery was catheterized on one side and ligated on the other. Then 65% Micropaque in 2% gelatin (10 to 15 cc) warmed to about 37°C was infused slowly (over 1 to 2 minutes) via the catheter, and the artery was ligated. The diameter of the Micropaque particles was about 0.1 μm. The infusion pressure was estimated by subtracting the open catheter pressure from the net pressure measured with the catheter in situ, and was kept at approximately 100 mm Hg. The brain was removed a few hours after injection and was immersed in 4% paraformaldehyde solution for 1 week.

In the first group of experiments (12 animals), the brain was cut in the coronal plane. A section 1 mm thick was cut parallel to the angle of the laser beam at the level of the laser exposure. After the section was photographed, a microangiogram of the sample was taken using a soft x-ray unit with a fine-grain film suitable for microscopic investigation. A histological section was prepared with hematoxylin and eosin (H & E) staining from the same section. Two animals without laser exposure were used as controls in this group. In a second group of eight animals, the brain was cut perpendicular to the laser beam at 1 to 2 mm from the cortical surface in the horizontal plane. The sections were prepared for histological examination with H & E staining.

Results

Macroscopic Findings

Animals tolerated exposure to the laser beam well, although three of the 18 animals showed apnea for 10 to 20 seconds immediately after. It was not rare to see bleeding from the focal area in CO₂ laser exposure (28% of 18 animals), which usually stopped spontaneously or on application of a small piece of cotton sheath. Bleeding was not observed in any of the 18 animals after Nd:YAG laser exposure.

Pathological Studies

After Nd:YAG exposure, a semilunar lesion was observed in the coronal sections (Fig. 1 left). A coagulation layer, chromatophilic on H & E staining, was located at the center of the lesion. A layer of edema surrounded the coagulation layer, and microcysts were found in the deeper portions of the edematous layer in 10 animals. Intravascular thrombus formation was sometimes found in the edematous layer. Hemorrhage was, however, observed microscopically in only one of 10 lesions. Sections perpendicular to the laser beam axis also

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% Soft x-ray unit manufactured by Soft X-Ray Unit, Inc., Tokyo, Japan.

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**FIG. 2.** Photomicrographs of sections perpendicular to the laser beam axis after Nd:YAG laser exposure at 20 W for 2 seconds. *Upper Left:* The extent of edematous layer surrounding the central coagulation layer is demonstrated. The margin was well demarcated from the surrounding normal brain tissue. H & E, x 34. *Upper Right:* Section from the edematous layer showing microcysts and shrunken vessels (arrow). H & E, x 85. *Lower:* Normal vascular filling is shown in the surrounding intact area. H & E, x 85.

showed the two coaxial layers (the coagulation layer and the surrounding edematous layer) which were well demarcated from the normal brain parenchyma. Shrunken vessels were typically found in both the edematous and the coagulation layers. Microcysts were found at the chromatophobic edematous layer. No bleeding occurred in this group of eight animals (Fig. 2).

After exposure to the CO₂ laser, a wedge-shaped lesion composed of a charred layer, a coagulation layer, and a surrounding edematous layer was observed around the central area of evaporated tissue (Fig. 3 left). In eight of 10 lesions, extravasation of red blood cells or sometimes massive hemorrhage was observed in the edematous layer and sometimes in the coagulation layer, which in 30% of the 10 cases resulted in bleeding into the central area of evaporated tissue. In the sections perpendicular to the laser beam axis, the three circular layers (charred, coagulation, and edematous layers) were observed radiating out from the lesion (Fig. 4 upper left). Dilated vessels were frequently found in the coagulation layer and sometimes in the edematous layer (Fig. 4 upper right). Some of these dilated vessels were thrombosed. Bleeding from these dilated vessels was often found in the surrounding brain parenchyma.

**Microangiographic Findings**

After exposure to the Nd:YAG laser, sections showed an oligovascular or avascular area which coincided with the edematous and coagulation layers in the histological sections from the same specimens (Fig. 1 center). Cortical vessels and perforator vessels in the area were thinner and the walls were irregular in shape compared with control sections (Fig. 1 right). The perforator vessels arched toward the avascular center of the lesion. No extravasation of contrast medium was found in this group.

Microangiograms of the brain section after CO₂ laser exposure showed a wedge-shaped avascular area (Fig. 3 right), which coincided with the coagulation layer in the histological section from the same specimen (Fig. 3 left). The cortical and perforator vessels adjacent to the avascular area were often dilated and congested, characteristics that disappeared abruptly at the coagulation layer. Extravasation of contrast medium into the avascular area was found in one case. The sections from control animals showed normal filling of contrast medium in the cortex beneath the craniectomy (Fig. 1 right).

**Blood-Brain Barrier Disruption**

In histological sections studied after Nd:YAG laser exposure, the Evans blue staining was semilunar in shape, and coincided well with the edematous layer (Fig. 5 left). The intensity was most prominent not at the surface of the lesion but in somewhat deeper
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FIG. 3. Left: Photomicrograph of a brain section after CO₂ exposure at 4 W for 2 seconds showing a wedge-shaped lesion composed of a coagulation layer and a surrounding edematous layer. H & E, × 40. Right: Microangiogram of the same specimen showing dilatation of the perforator vessels around the wedge-shaped lesion, × 40.

Discussion

Neurosurgeons are sometimes obliged to operate through a very narrow entrance to remove a lesion that lies close to functional structures. The laser can be very helpful in these situations as it permits precise dissection and evaporation of these lesions without damaging surrounding structures.⁴

Since the CO₂ laser was introduced into our neurosurgical clinic in 1979, the clinical and laboratory effectiveness of laser surgery has been studied.⁷ Although the earlier results were encouraging, the major disadvantage of the CO₂ laser was an insufficient hemostatic capability. The Nd:YAG laser, which was reported to be useful for hemostasis,¹²,¹³,¹⁴ was added to our neurosurgical instrumentation in 1982. Since then, we have been studying the effect of the two different laser beams on normal brain tissue.¹⁴ These experiments were conducted using the same power and time of laser exposure as are frequently used in our clinic and have been found practical and useful.

In the histological examination, the most striking difference between the two laser sources was in regard to vascular changes. Hemorrhage was rare and vessels were shrunken and tapered following Nd:YAG exposure, whereas they were dilated and congested, with occasional hemorrhage, following CO₂ exposure. Microangiography was used to show the microvascular changes in the laser-induced lesions in detail. Micropaque was filtered before injection, and the particles used were 0.1 μm in diameter, which was small enough to reach the capillaries. Infusion pressure was monitored to minimize any deviation among the animals. The results of microangiography were basically compatible with the histological investigation. The vessels in the edematous layer (which was usually oligovascular) were thin and tapered following Nd:YAG exposure, whereas they were dilated in the area adjacent to the avascular area of evaporated tissue following CO₂ laser exposure.

The characteristics of the Nd:YAG laser beam in clinical use on neuronal tissue when compared to the CO₂ laser beam can be summarized as follows:⁶,¹⁶ 1) selective absorption by blood: the Nd:YAG laser is reported to have a 100:1 blood:brain absorption ratio,¹⁶ which causes a selective thermal effect on cerebral vessels after laser beam exposure; 2) high scattering tendency: the Nd:YAG laser beam scatters more widely than the CO₂ laser; and 3) deeper penetration and less absorption by neuronal tissue. From our results and the characteristics described above, the mechanism...
FIG. 4. Photomicrographs of sections perpendicular to the laser beam axis after CO₂ laser exposure at 8 W for 2 seconds. *Upper Left:* The charred layer, coagulation layer, and edematous layer are observed radiating coaxially around the central tissue defect. H & E, × 34. *Upper Right:* Higher magnification of the coagulation and edematous layers showing the dilated vessels (arrow) and hemorrhage around the vessels. H & E, × 85. *Lower:* Section of normal brain tissue surrounding the lesion in the same specimen. There is normal filling of the vessels with contrast medium. H & E, × 85.

FIG. 5. Schematic drawings showing Evans blue discoloration after laser exposure, indicating the disruption of the blood-brain barrier after Nd:YAG laser exposure (left) and after CO₂ laser exposure (right).

of hemostasis and coagulation by the Nd:YAG laser can be summarized as follows. When the laser beam penetrates the cortex, it scatters in various directions and is absorbed selectively by blood cells which contain more chromatin than other cells in the brain parenchyma. When the absorbed energy turns to heat, thermal shrinkage of collagen fibers in the vessels takes place (as shown by Gorisch and Boergen, unpublished data, 1979), resulting in vessel occlusion. Aggregation of blood cells results in intraluminal occlusion, as reported by Boergen, et al., and may be a possible reason for obstruction of vessels (Fig. 6). Hemostasis is the result of these pathological events after Nd:YAG laser exposure. Vasogenic edema following the damage to the blood-brain barrier caused by the thermal coagulation is well known, and causes edema in the laser-induced lesion. Thus, despite the wide extent of the lesion, post-exposure hemorrhage is rarely observed, as the laser beam effect is primarily on the vascular component, causing hemostasis; the neuroglial component, which has relatively low absorption coefficient, sustains less damage after Nd:YAG laser exposure.

In CO₂ laser exposure, the laser beam coagulates the brain and evaporates the tissue. However, because of less scattering and less absorption by blood, vessels adjacent to the coagulation layer do not shrink or become obliterated; instead, they become dilated and congested. As shown microangiographically and histologically in our experiments, the normal blood flow is interrupted sharply at the coagulation layer. Bleeding may take place when intraluminal pressure is high enough to break the fragile vessels at the edge of the laser beam axis.

Combined coaxial exposure might overcome the disadvantages of each laser beam. Cutting with less bleeding was achieved to some extent in our studies by using combined coaxial exposure. The frequency of
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FIG. 6. Schematic drawings showing the changes in the microvasculature after Nd:YAG laser exposure (left) and CO2 laser exposure (right).

hemostasis, which was only 18% with CO2 laser exposure, was three times higher when 20 W of Nd:YAG laser beam was combined coaxially.

The effect of the CO2 laser on cerebral microcirculation was investigated by Toya, et al., using fluorescein angiography. They observed a circular zone of nonfilling with fluorescein dye which coincided with the coagulation layer. Edema, rupture of capillaries, and thrombus formation were reported in the area surrounding the nonfilling zone. Our findings relating to the effect of the CO2 laser on the microcirculation in the vicinity of the laser beam axis are basically in agreement with theirs. The results of this study provide some basic understanding of the microvascular changes following laser beam irradiation. Further studies and an accumulation of basic knowledge will be necessary to determine the mechanisms responsible for these findings and to help improve the application of laser beam techniques for clinical neurosurgery.

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References


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