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Application of a flexible CO_2 laser fiber for neurosurgery: laser-tissue interactions

Laboratory investigation

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Object. The CO_2 laser has an excellent profile for use in neurosurgery. Its high absorption in water results in low thermal spread, sparing adjacent tissue. Use of this laser has been limited to line-of-sight applications because no solid fiber optic cables could transmit its wavelength. Flexible photonic bandgap fiber technology enables delivery of CO_2 laser energy through a flexible fiber easily manipulated in a handheld device. The authors examined and compared the first use of this CO_2 laser fiber to conventional methods for incising neural tissue.

Methods. Carbon dioxide laser energy was delivered in pulsed or continuous wave settings for different power settings, exposure times, and distances to cortical tissue of 6 anesthetized swine. Effects of CO_2 energy on the tissue were compared with bipolar cautery using a standard pial incision technique, and with scalpel incisions without cautery. Tissue was processed for histological analysis (using H & E, silver staining, and glial fibrillary acidic protein immunohistochemistry) and scanning electron microscopy, and lesion measurements were made.

Results. Light microscopy and scanning electron microscopy revealed laser incisions of consistent shape, with central craters surrounded by limited zones of desiccated and edematous tissue. Increased laser power resulted in deeper but not significantly wider incisions. Bipolar cautery lesions showed desiccated and edematous zones but did not incise the pia, and width increased more than depth with higher power. Incisions made without using cautery produced hemorrhage but minimal adjacent tissue damage.

Conclusions. The photonic bandgap fiber CO_2 laser produced reliable cortical incisions, adjustable over a range of settings, with minimal adjacent thermal tissue damage. Ease of application under the microscope suggests this laser system has reached true practicality for neurosurgery. *(DOI: 10.3171/2009.7.JNS09356)*

Key Words • **carbon dioxide laser** • **laser surgery** • **optical fiber** • **swine**

Surgical lasers form a mainstay of treatment in many disciplines, including ophthalmology, dermatology, dentistry, plastic surgery, otolaryngology, and head and neck surgery.[1,6,13,17,19] In contrast, lasers tend to be used infrequently in most neurosurgical operating rooms, despite early optimism regarding the application of this technology shortly after its development. For example, Stellar et al.[20] reported the first resection of a glioblastoma multiforme using a CO_2 laser in 1970, and commented that its use for "additional otherwise hopeless human brain tumours is now warranted." Perhaps the strongest endorsement came from Ascher and Heppner[3] who identified numerous indications for the CO_2 laser in both central and peripheral surgical cases, and remarked that the only contraindication to use of the laser "occurs if somebody uses the laser to solve his Ego problems."

Unfortunately, cumbersome ergonomics of the CO_2 laser have limited its widespread use. Its long wavelength (10.6 μm) prevents its transmission using standard fiber optic cables, and bulky articulating arms with mirrors are required to transmit sufficient energy to the surgical site in direct line of sight, restricting freedom of movement.[18] Moreover, resecting a tumor requires constant refocusing of the CO_2 beam if it is coupled to a microscope. Without fiber optic delivery, use of a CO_2 laser through an endoscope is impossible. These shortcomings have kept most neurosurgeons from adopting the CO_2 laser as a regular surgical tool, despite its many potential benefits.

Dielectric mirrors are able to efficiently reflect light through a narrow range of incident angles with low absorption losses.[10] The existence of an omnidirectional reflection band allows a dielectric surface to reflect light of any incident angle, known as omnidirectional reflectance.[11] A hollow optical fiber has been created that is lined with an interior omnidirectional dielectric mirror that has a photonic bandgap for the transmission of CO_2

Abbreviations used in this paper: GFAP = glial fibrillary acidic protein; PBF = photonic bandgap fiber;

laser light with low absorptive losses.[22] This PBF assembly allows for the flexible delivery of CO_2 laser energy in a range of power settings similar to those used for surgical applications with rigid delivery systems, but with the advantage of using a laser delivery apparatus that is on a small scale and does not use a large, inconvenient assembly.

This is the first histological study to assess a newly developed tool that allows for the flexible delivery of CO_2 laser energy to brain tissue. The differences between a focused, line-of-sight, free-space optical beam and a handheld fiber with a 320-μm aperture and no focal plane are subtle but important. The purpose of this study was to demonstrate that these differences do not impact the qualitative nature of the laser-tissue interaction and to assess the handling characteristics of the PBF CO_2 laser on the brain tissue of a large animal, simulating its use in humans. Specifically, experiments were conducted using a swine craniotomy model to compare cortical incisions created using the laser with other incisions created using conventional means, such as bipolar cautery using microscissors, as well as a scalpel.

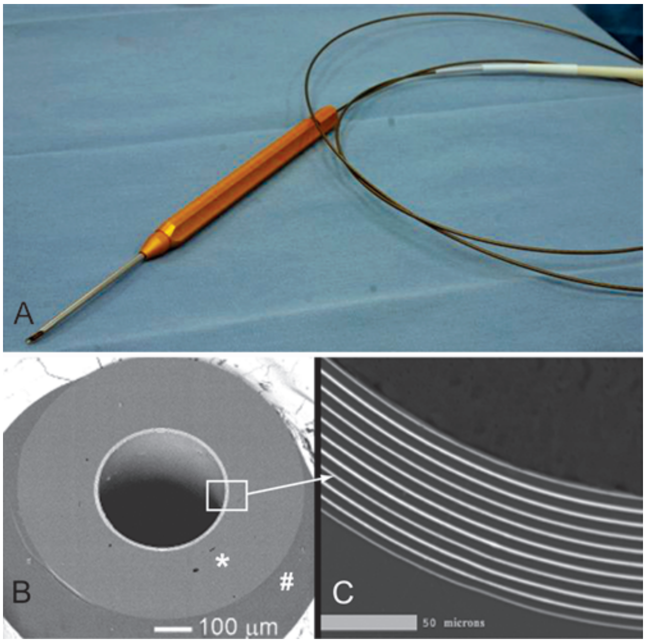

Fig. 1. Photographs of the CO_2 laser system. **A:** The PBF assembly, consisting of the BeamPath Neuro-L fiber passing through the handheld guide. Note the fiber is slightly recessed in the guide, allowing the distal tip to be used as a nonenergized dissector. **B:** Cross-section of the BeamPath fiber as viewed under a scanning electron microscope. The hollow core *(black)* is noted at the center of the fiber, surrounded by the layers of mirror *(white)* that line the core circumferentially. The mirror is embedded in a cyclo-olefin copolymer fiber cladding (*), and surrounded by epoxy (#). **C:** Higher magnification of the mirror layers of the BeamPath fiber. This novel architecture allows the propagation of CO_2 laser energy through a flexible fiber.

Methods

Photonic Bandgap Fiber Setup

The PBF used for these experiments (Fig. 1) consisted of a disposable hollow core fiber (BeamPath Neuro-L fiber, OmniGuide Inc.) connected to a CO_2 laser source (Lumenis Compact Series 30C, Lumenis Ltd.). The fiber used had an outer diameter of 1.2 mm and produced a 320-μm laser spot size at the tip. Laser energy was adjusted from 2 to 20 W, in continuous wave or pulsed mode. Before use in experiments, the laser output power was checked to ensure proper calibration, and the fiber was positioned in a handpiece.

Study Ethical Approval

This study was conducted at the Neurosurgery Research Laboratories in the Division of Neurological Surgery of the Barrow Neurological Institute and St. Joseph's Hospital and Medical Center, with experimental approval from the St. Joseph's Hospital and Medical Center's Institutional Animal Care and Use Committee.

Laser Application to Cortex

Six adult female swine were used for this study. Under deep general inhalant anesthesia using a cuffed endotracheal tube, a craniotomy was performed to widely expose both cerebral hemispheres. In 4 animals (8 hemispheres), a positioning device was used to hold either the laser handpiece, or a Malis CMC-III Bipolar Cut and Coagulation System (tips fixed at 0.5-mm separation; Codman and Shurtleff, Inc.) in 90° approximation to the most prominent portion of a cortical gyrus. Laser or bipolar cautery energy was then delivered for a specified power setting and time duration (Table 1). The lesion points were marked with India ink and fixed with acetic acid for later identification during histopathological assessment. The region of the gyrus containing the lesion was then resected with a wide margin and immediately placed in 10% formalin for histopathological analysis.

In 2 animals (4 hemispheres), incision lines were created by freehand application of the laser fiber within its handpiece (2 and 7 W), Malis bipolar cautery (with and without microscissor incision of pia), or a No. 11 scalpel blade. Incisions were 1 cm in length, in the center of the gyrus. In 2 hemispheres, the gyri were resected with a margin around the incision line and immediately placed in 10% formalin for histopathological analysis. In the other 2 hemispheres, the gyri were resected with a margin around the incision line and immediately placed in a 2.5% glutaraldehyde solution for electron microscopy. At the conclusion of the experiments, the animals were killed while still under deep anesthesia.

Light and Electron Microscopy

Tissue samples fixed in formalin were stained with H & E for light microscopy and lesion zones were characterized and measured (Fig. 2A and B). For laser incisions, the total depth of the incision was measured to the deepest point of tissue effect (bottom of edematous zone), the desiccated depth was measured to the deepest point of desiccated tissue (between desiccated and edematous zones), and the crater depth was measured to the deepest point at which all tissue had been vaporized. For bipolar cautery lesions, total depth and desiccated depth were measured, but no craters were present. In addition, the total area of affected tissue (desiccated and edematous) was calculated for each energy modality and compared with the depth of coagulation achieved (Fig. 2C and D). To assess cell viability and the extent of axonal damage, formalin-fixed samples were stained with a Sevier-Munger silver stain. Immunohistochemical analysis for GFAP was also performed to assess for brain reactivity, scarring, and gliosis using astrocyte identification.

Tissue samples fixed in glutaraldehyde were washed with neutral phosphate-buffered saline after 24 hours. Hydrated specimens were cut to size and mounted on slides, and using the low-pressure (4.0 Torr), wet-environment setting, scanning electron microscope images were recorded. Samples were then postfixed in osmium tetroxide and critical-point dehydrated with an ascending series of alcohol concentrations. The samples were mounted on slides and sputter-coated with gold. Using a vacuum, images were acquired using standard scanning electron microscopy at low- and high-power magnification, and lesion zones were characterized.

Results

The gross appearance (Fig. 3) of all incisions was consistent among separate applications. Focused laser energy produced clean pial incisions without hemorrhage, and depth increased as a function of wattage. Defocused laser energy produced wide, charred pial incisions. Bipolar cautery energy produced a blanched, coagulated pial surface that was not incised, but could be cut with microscissors without bleeding. Scalpel incision of the pia produced a smooth line with hemorrhage.

Light microscopy of laser incisions (2 and 7 W; Fig. 4A and B) revealed 3 typical zones as previously described, including a central crater, a zone of desiccated tissue, and a zone of edematous tissue.[2] Scanning electron microscopy of laser incisions at low magnification showed an elevated rim of desiccated tissue, and crater depths increasing with increased laser output, while at higher magnification desiccated tissue was observed with no blood cells or debris.

Light microscopy of bipolar cautery lesions revealed desiccated and edematous zones, with no crater or incision, and width increased more than depth with higher power settings. Scanning electron microscopy revealed only desiccated tissue on the cortex in the area of bipolar cautery application (Fig. 4C). Bipolar cautery lesions that were cut using microscissors showed irregular pial incisions with small areas of hemorrhage (Fig. 4D). Scalpel incisions of the pia were linear (Fig. 4E), and because there was no coagulation, there was hemorrhage on both light microscopy and scanning electron microscopy, but normal tissue architecture was preserved. Scanning electron microscopy images of hydrated tissue samples also demonstrated regular, well-defined edges of laser incisions that were deeper with increased power (Fig. 5A and B). In contrast, bipolar cautery lesions cut with microscissors had an irregular appearance (Fig. 5C), and scalpel incisions revealed blood in the wound (Fig. 5D).

TABLE 1: Power settings, duration, and distance to the cortex used to deliver laser or bipolar energy to the swine brain

Energy Modality	Power Setting	Duration (sec)	Distance to Cortex (mm)
CO_2 laser	7 W	0.1	0
CO_2 laser	7 W	0.2	0
CO_2 laser	11 W	0.1	0
CO_2 laser	11 W	0.2	0
CO_2 laser	15 W	3	7.5
CO_2 laser	15 W	3	25
CO_2 laser	15 W	4	50
bipolar cautery	30 Malis	2	0
bipolar cautery	40 Malis	2	0

Silver staining using the Sevier-Munger technique clearly demonstrated axons in the desiccated and edematous zones and immediately adjacent to the scalpel incision line (Fig. 6 *left* and *center columns*). In the region around the scalpel incision, axons demonstrated a normal shape with no evidence of injury or swelling (Fig. 6E). Similarly, axons in the edematous zone of the 2-W laser incision had a normal appearance, while in the desiccated zone, occasional axonal balloons were observed, suggesting increased temperature in this area with some damage to passing fibers (Fig. 6A). Both of the bipolar cautery lesions demonstrated occasional axonal swellings and balloons in the desiccated and edematous zones, but because most of the injured area was superficial to the white matter tracts, most of these deeper axons were spared (Fig. 6C and D). Axons in both the desiccated and edematous zones of the 7-W laser incision showed signs of swelling and balloons, indicative of injury, with greater numbers closer to the central crater, reflecting the higher thermal energy in this region (Fig. 6B). No injured axons were observed beyond the edematous zone in any of the lesions. Immunohistochemical analysis for GFAP revealed no reactive astrocytes in any of the lesions (Fig. 6 *right column*), likely reflecting the short time interval between creation of the incisions and resection of the tissue.

With increasing laser power output, there was a trend of increasing depth of all 3 zones, but minimal increase in width. In contrast, when bipolar cautery energy was applied at higher power, it produced wider but not deeper zones (Fig. 7A and C). When the CO_2 laser was applied with a defocused beam (from set distances above the cortex), it created wider, shallower zones of desiccation and edema, similar to the lesions produced by the bipolar cautery (Fig. 7B and D).

When examined as a function of depth of coagulation (Fig. 8), it was observed that the total area of tissue affected by thermal energy was much higher when using bipolar cautery compared with the CO_2 laser, confirming the minimal adjacent injury expected with laser incisions. Higher power settings of the laser, although creating deeper incisions, did not appreciably increase the area of lateral thermal damage.

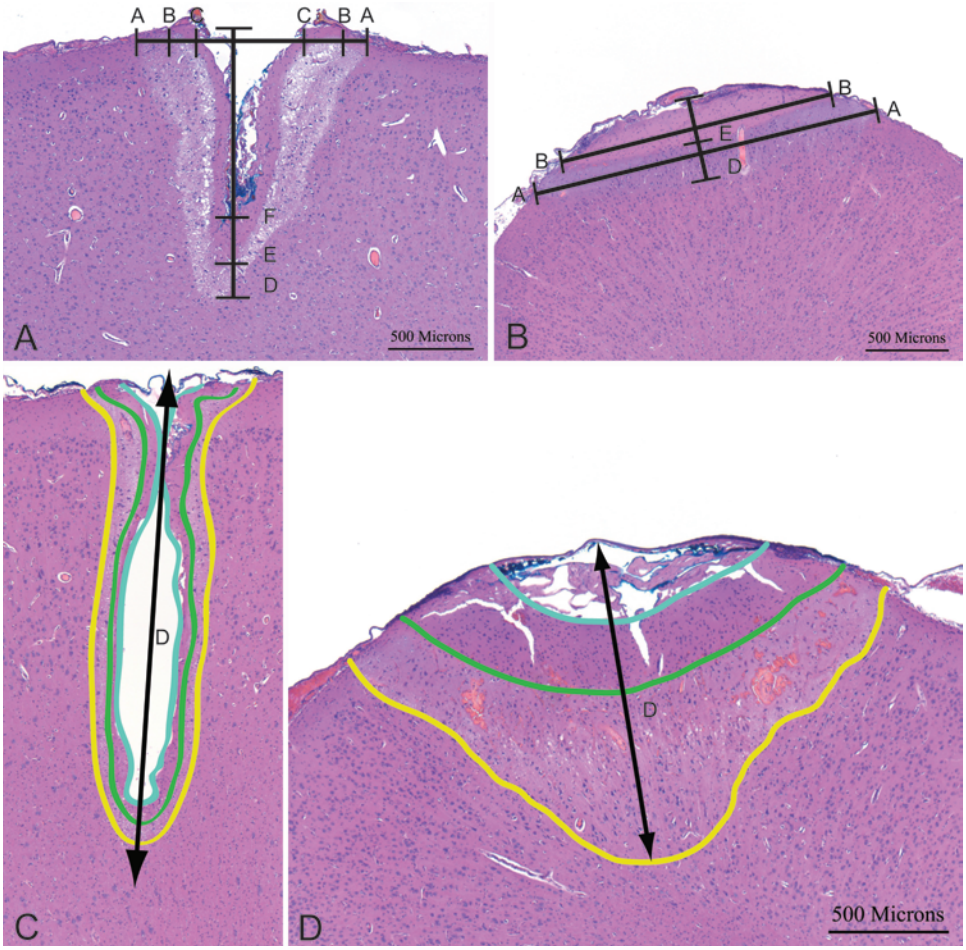

Fig. 2. Photomicrographs of tissue affected by the laser **(A and C)** and bipolar cautery **(B and D)** systems. The ***upper panels*** **(A and B)** demonstrate measurements used for evaluating the width and depth of tissue affected by application of laser **(A)** and bipolar cautery **(B)** energy to the surface of the brain. Measurement indicators: A = width of edematous zone (total width); B = width of desiccated zone; C = width of crater; D = depth of edematous zone (total depth); E = depth of desiccated zone; F = depth of crater. The ***lower panels*** **(C and D)** show identification of the area of secondary thermal injury (between the *blue* and *yellow lines*) of tissue affected by the laser **(C)** or bipolar cautery **(D)** systems compared with the total depth of tissue affect (D = total depth). The region above the *blue line* corresponds to the area of primary thermal injury; the region between the *blue* and *green lines* corresponds to the desiccated zone; the region between the *green* and *yellow lines* corresponds to the edematous zone.

Discussion

Properties of Surgical Lasers

The properties of both the laser and the affected tissue are important in determining laser-tissue interactions. Laser properties include wavelength (determined by the lasing medium, such as CO_2), power output (watts), beam density (spot size), and time of exposure.[25] Together, these factors determine the energy density (watts/cm^2 × time) delivered to the tissue.[9] Important properties inherent to the tissue itself include the absorption coefficient (absorbed light is rapidly converted to heat), the extinction length (the depth light will penetrate), and the presence of light-absorbing chromophores such as water, hemoglobin, or melanin.[26] Together, laser and tissue factors determine the rate of tissue heating, area of laser effect, and the type of lesion created.[14]

Despite the advantages provided by use of the CO_2 laser such as its precision, no-touch dissection, avoidance of retraction, relative hemostasis, and sterilization with cutting, its use in the neurosurgical operating room has not been widespread because of the requirement of direct line-of-sight for energy transmission with standard equipment. Previous work has explored the role of the laser in both laboratory and clinical settings, with many favorable findings, but the lack of an easily manipulated delivery device has remained a major hindrance.

Comparison of Incisions Produced by Different Modalities

Similar to previous work with rigid CO_2 line-of-sight laser systems, the flexible CO_2 laser fiber used in this study produced consistent incisions with narrow, well-defined areas of surrounding desiccation and edema, demonstrating similar CO_2 wavelength characteristics and tissue interaction.[2] Consistent with the high absorption of CO_2 laser energy in tissue, thermal tissue injury lateral to the incision was minimal and did not increase significantly with higher power settings. In contrast, the pattern of tissue effect after application of bipolar cautery energy was wider but not as deep, and the pia remained intact. Cortical areas that had bipolar cautery energy applied could be incised with minimal bleeding, with brisk bleeding from noncauterized incisions. When the laser was applied to the brain surface from a distance (defocused laser), the resulting lesion was similar to that produced by the bipolar laser, with no well-defined crater, and wider, shallower zones of desiccation and edema, suggesting it could cauterize tissue when used in this manner. As a surrogate marker for cell viability, silver staining was performed. When axons suffer thermal injury, they develop swelling and balloons, and these nerve fibers are vulnerable to degeneration and death. It was noted that axonal swelling was only observed to a significant degree at 7-W laser power, and only within the narrow zones of desiccated and edematous tissue. Even at this higher laser power, axonal changes were minimal in a large number of neurons in the edematous zone (and in nearly all neurons at lower laser power), suggesting a high degree of cell survival adjacent to laser application.

The aim of this study was not to demonstrate superiority of one modality or the other, but rather to compare and contrast the tissue effects of 2 complimentary thermal-energy delivery modalities, the CO_2 laser and bipolar cautery, as well as incisions made without heat energy, using a scalpel and microscissors. The fundamental difference between laser surgery and electrosurgery—rapid conversion of electromagnetic radiation to heat for the laser, and conversion of alternating current electrical energy to heat between the tines for bipolar cautery—produces the characteristic lesions described above, and each has advantages and disadvantages.

The same surgical instrument can often be applied in a number of different ways to achieve a similar end, and such use tends to be operator-dependent and can vary widely among surgeons. For example, when creating an initial pial incision, some surgeons may choose to drag the bipolar forceps with both tines in contact over the cortical surface, creating a coagulation zone that can then be incised, while others may choose to incise and then coagulate the pia with 1 bipolar tine above and 1 below the surface. Both methods achieve acceptable hemostasis, but also highlight the need for a 2-step approach, with separate coagulating and cutting of the tissue. On the other hand, the laser is able to both cut and coagulate, provided cortical vessels > 1 mm are not encountered, which is the limit of this laser's coagulating capabilites.[8] This characteristic reflects the laser's efficiency as a tool for incision and resection while maintaining a dry operative field, but emphasizes the role of bipolar cautery as the primary instrument for coagulation.

Another common use of the bipolar forceps is for nonenergized dissection by spreading or grasping tissues, such as arachnoid adhesions or developing tumor planes. A major advantage of the flexible CO_2 laser fiber over conventional CO_2 laser systems is the ability to use the handheld guide (which has a small, rounded tip with a profile similar to many microdissectors) as a nonenergized dissecting tool, easily manipulated under the microscope, and without the need to change instruments when laser power is required.

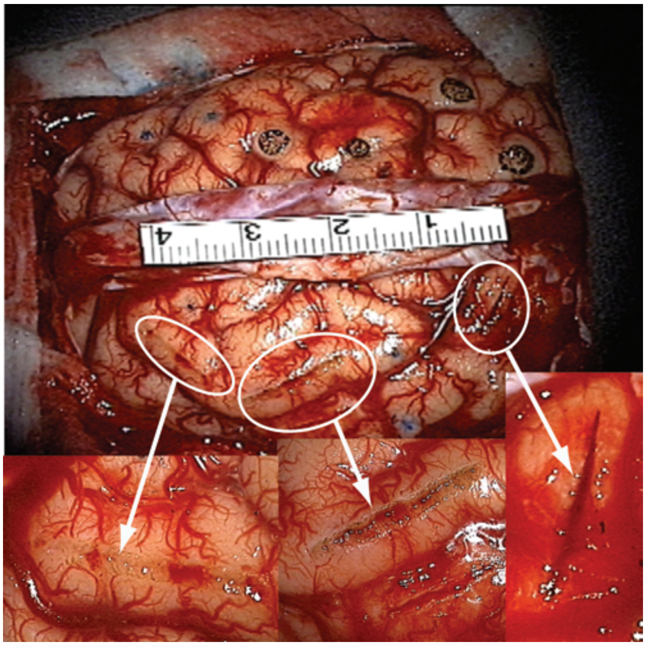

Fig. 3. Photographs showing the gross appearance and size of pial incisions made by different cutting modalities. *Left circle* and *enlargement* shows a 2-W laser incision; *middle circle* and *enlargement* shows a 7-W laser incision ***(top)*** and bipolar cautery line cut using microscissors ***(bottom)***; *right circle* and *enlargement* shows a scalpel incision. The *dark circles* on top (above the ruler) were made with a defocused laser beam, by holding the laser a predetermined distance above the cortex.

Whereas bipolar cautery is the mainstay treatment for achieving coagulation, it is not a cutting instrument, and has certain limitations, such as the need for direct application of the forcep tines to the tissue to deliver current. This can lead to a buildup of char and coagulum that can stick to and tear tissues, causing bleeding. The laser, while unable to coagulate large vessels, can deliver thermal energy without the need for contact, and may prove efficacious for managing diffuse bleeding from small vessels such as in a tumor bed. As with any laser, the fiber-enabled system often produces smoke, which is not usually a problem with bipolar cautery. Unique to the fiber is the constant flow of inert helium gas that flows through the hollow core and cools the fiber. This gas flow also serves to clear most of the smoke plume from the target area, although suction may also aid in evacuation of smoke.

When making an incision, the cutting edge of a scalpel blade forces tissue apart along a cleavage plane created by its downward mechanical force, below the surface of the tissue, and is not directly visible. As no other energy is applied, a scalpel creates virtually no lateral tissue effect; however, the operator must carefully control the depth of the cut by feel, as it is a blind maneuver. For example, our histological analysis revealed much deeper incisions made with the scalpel than we anticipated from

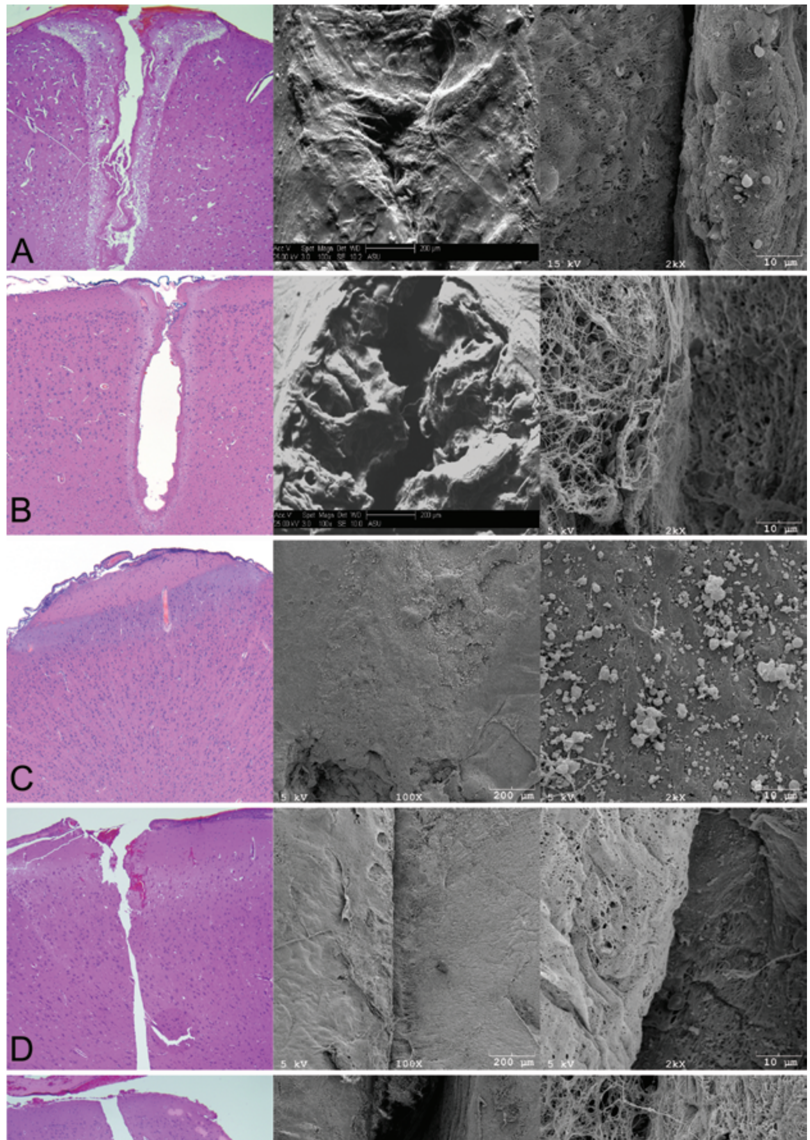

Fig. 4. Photomicrographs of tissue samples after a 2-W laser incision **(A)**, 7-W laser incision **(B)**, bipolar cautery **(C)**, bipolar cautery with microscissor incision **(D)**, and scalpel incision **(E)**. H & E, original magnification × 40 *(left column)*. Scanning electron microscopy, original magnification × 100 *(center column)* and × 2000 *(right column)*.

observation of the gross incision lines on the cortex, suggesting this may be a common occurrence despite careful application of the blade.

In contrast, an incision created by a laser beam can be directly observed, and the shape of the cut will be largely determined by the power settings of the device. However, while the physical properties of CO_2 energy dictate its superficial absorbance in tissue, continuous application of a laser beam in 1 location will penetrate through the tissue and thus care must be taken to avoid inadvertent injury to underlying structures. Such complications can be avoided by movement of the laser with ongoing observation of its effects, or using short pulses.

Similar to the laser, the tips of the bipolar cautery system can be directly visualized when the device is being used, and alternating current passes only between the tips. The lateral thermal effect, however, may extend beyond the area of the tips, as observed by histological

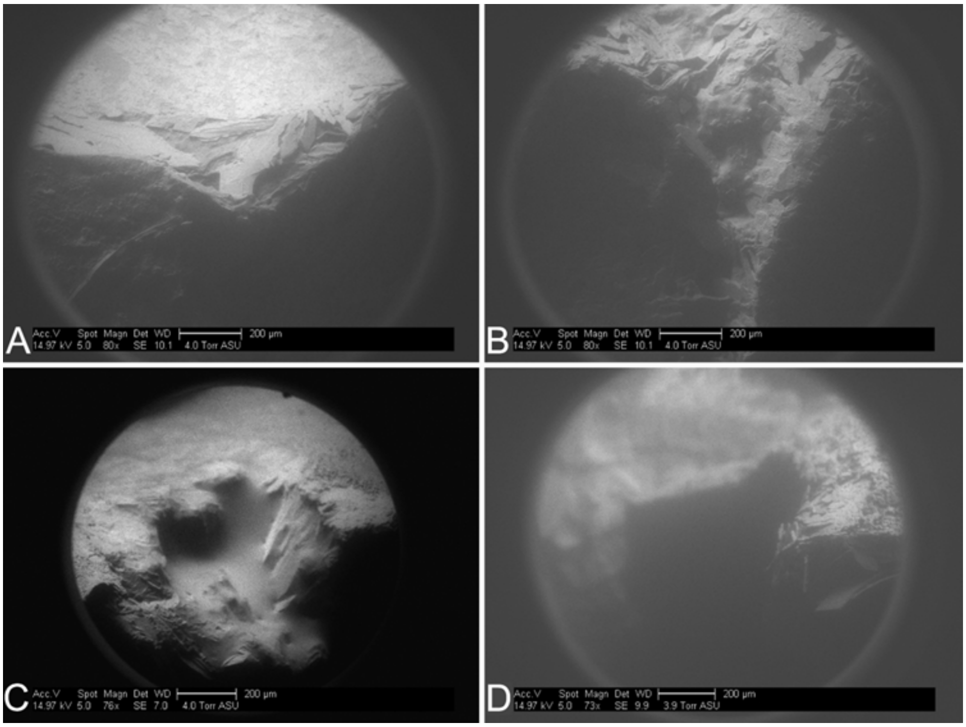

Fig. 5. Images acquired using scanning electron microscopy of hydrated tissue samples using a low-pressure, wet-environment setting. The incisions produced by the CO_2 laser at 2 W **(A)** and 7 W **(B)** have regular borders, and the higher laser power produced a deeper incision. The bipolar cautery lesion incised using microscissors **(C)** has an irregular, widened border. The scalpel incision **(D)** is dark with blood products, and an organized clot can be observed near the surface of the cortex.

analysis in these experiments, and this lateral spread increases with bipolar cautery power and duration. By simulating the electrical distribution between the tines of the bipolar forceps and the impedance of the tissue, this effect can be accurately modeled, showing a wide, shallow lesion similar to that observed using histology in our study (Fig. 9). This finding has a clinical correlate in surgery around the cranial nerves such as in acoustic neuroma resection, in which bipolar cautery use may trigger changes in electrophysiological recordings despite not being applied directly to the nerve. The more narrow lateral thermal spread of CO_2 laser energy may be advantageous in such situations.

Utility of the CO_2 Laser for Neurosurgery

The CO_2 laser has a wavelength of 10.6 μm, and is highly absorbed in tissue and water, independent of pigments. This high absorption results in rapid conversion of light to heat in a very small volume of tissue, with minimal penetration to surrounding areas.[26,27] This profile makes the CO_2 laser an excellent cutting tool when using a focused beam, and allows for some hemostatic capabilities with a wider defocused beam, with minimal thermal damage to adjacent tissue, which is ideal for neurosurgical purposes.[8]

When making observations of the lesions produced by different energy sources on the brain, it is natural to evaluate and attempt to compare them. Cozzens and Cerullo[5] found that less Evans blue dye (a marker for blood-brain barrier disruption) was extravasated around laser lesions in the cat cortex than around bipolar coagulation cut with sharp dissection. These authors acknowledged that the laser and bipolar cautery are often used in different roles; however, the laser could offer the potential to reduce postoperative morbidity, and they suggested enthusiasm for it was similar to that for the introduction of the Bovie electrosurgical unit in 1930.[5]

Other early studies were also encouraging about the use of the laser, and identified its advantages and indications for use.[3,4,21] In their 1996 review of the use of lasers in neurosurgery, Devaux and Roux[8] were supportive, stating that lasers play a large role in the neurosurgical armamentarium. In sharp contrast, Laws commented on this review, downplaying the importance of the laser, and said "I cannot think of a single case that I would cancel if the laser were broken and it is hard to remember the last time I used a laser in clinical surgery."

Clearly there is a wide range of opinions based on experience with laser systems, and it is likely that the ease of use and ability to manipulate the device are factors that determine whether the laser has utility in the neurosurgical operating room. In some situations, such as the stereotaxically directed system described by Kelly et al.,[15,16] the laser mounted on the microscope assisted in precise intraparenchymal tumor resections. Although the laser beam is invisible, falling in the infrared spectrum, several guidance systems have been used for accurate direction of the beam, such as a helium neon pilot laser when attached to the microscope. While the current PBF lacks a secondary visible laser, the constant stream of helium gas can be

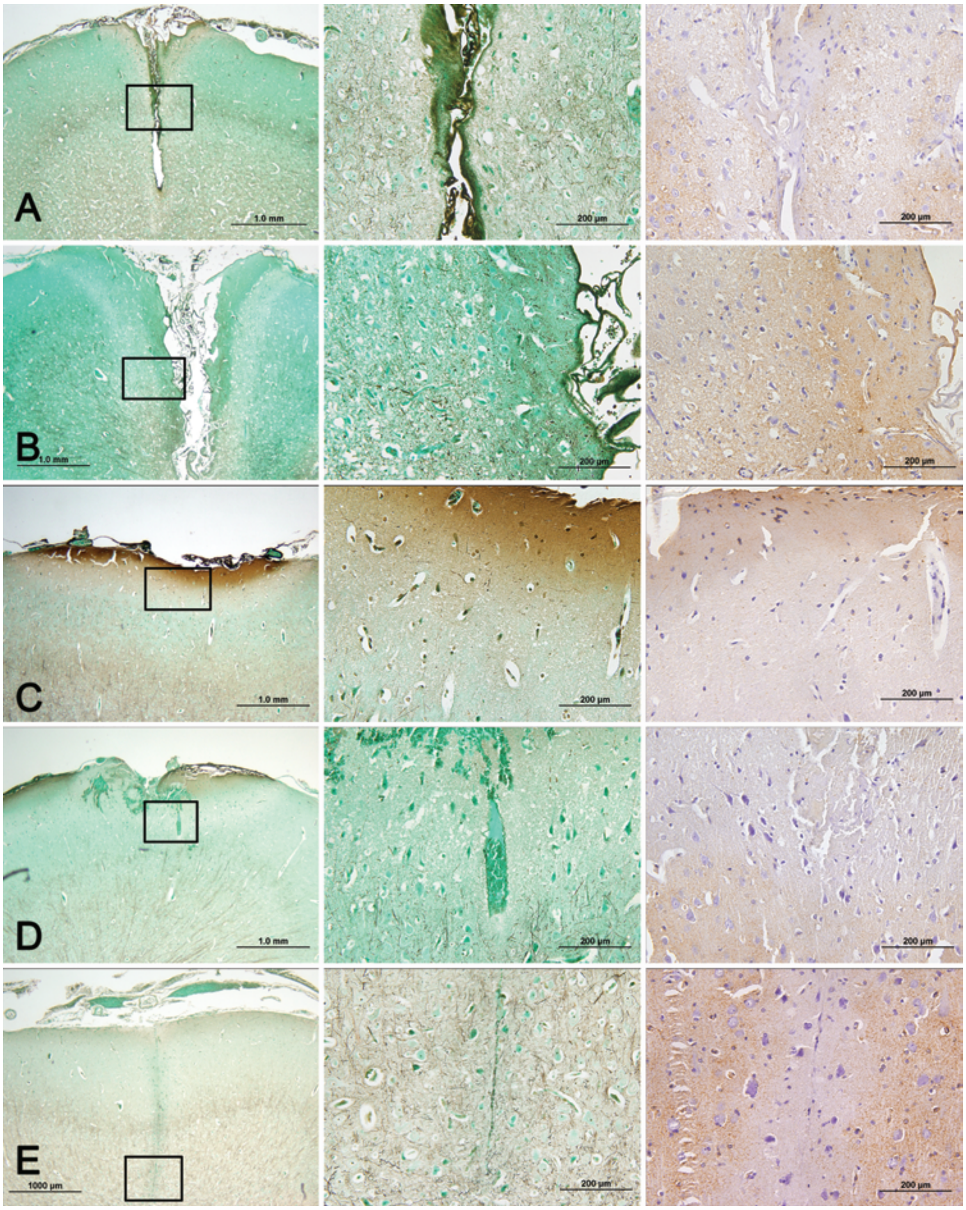

Fig. 6. Photomicrographs of tissue samples from the 5 different incision methods used in the study. The lesions represented are 2-W laser incision **(A)**, 7-W laser incision **(B)**, bipolar cautery **(C)**, bipolar cautery with microscissor incision **(D)**, and scalpel incision **(E)**. The location of the higher magnification images is indicated by the *box outline* in the *left column.* Sevier-Munger silver stain, original magnification × 40 *(left column)* and × 200 *(center column).* Glial fibrillary acidic protein, original magnification × 200 *(right column).*

used for aiming as it produces a slight depression in most tissues and surfaces. In addition, because the energy is delivered by the fiber that in most cases is immediately adjacent to tissue, there is excellent control over location of energy application.

As in many other situations, full freedom of movement, such as that provided by the PBF laser system, could be of great benefit in microsurgical applications. The fiber is introduced into a handpiece that is easy to wield and has a small profile, allowing the surgeon to use it in confined regions and through narrow exposures. Unlike the line-of-sight CO_2 laser, which involves a focusing lens and thus a focal plane, the CO_2 beam emerging from the fiber defracts through its core and expands as a function of distance. Thus, surgeon control of spot size, and therefore to an extent penetration into tissue, is achieved simply by controlling the distance from the tissue.

The small size of the fiber also allows it to fit inside most endoscopes, and it has been used in this way in the field of otolaryngology and head and neck surgery.[7,12] In light of the many advances in endoscopic neurosurgery, this could be another promising application of the laser fiber. Because of high water absorption, CO_2 laser energy does not travel through fluids, but rather is quickly converted to local heat. This necessitates a dry operative field when using the laser, and presents challenges for use in

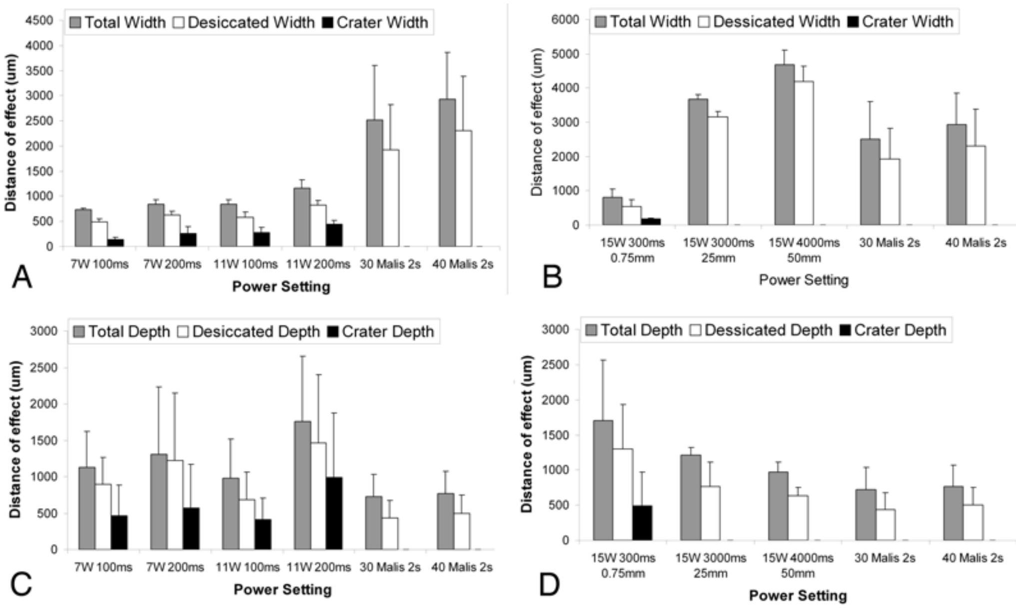

Fig. 7. Comparison of width **(A and B)** and depth **(C and D)** measurements for various laser powers, durations, and distance settings, and bipolar cautery power settings. When held at a distance above the tissue, as a defocused beam **(B and D)**, the laser created coagulation zones similar to the bipolar cautery with no obvious crater. When held in approximation to the tissue, as a focused beam **(A and C)**, the laser created a well-defined crater with predictable adjacent zones of desiccation and edema.

CSF spaces such as during endoscopic ventriculostomy, although at the same time the fluid medium may serve as a protective barrier. One technique to use lasers during endoscopy in the ventricles has been to use a ball tip that converts the light energy to thermal energy; however, this purpose was mostly to reduce the risk of high-power neodymium:yttrium-aluminum-garnet laser light damaging adjacent brain.[23,24,28] The availability of the CO_2 laser, with its safer tissue absorption profile, would allow direct use in the ventricle if a means of providing a dry path to the target can be found, such as by bubbling gas through the delivery fiber or by partial drainage of CSF.

A limitation of the current study is the restriction to examination of normal cortical tissue. In practice, a major application of laser energy is for resection and ablation of tumor tissue, which we were unable to assess at this time. However, given the similar water content of most biological tissue, including tumor and cortex, it can be assumed that the energy absorption profile and lateral thermal spread will also be similar. Further, the use of the laser for creating precise corticotomies near eloquent regions or for general cortical extirpation in tumor or epilepsy surgery would be supported by the findings of this study.

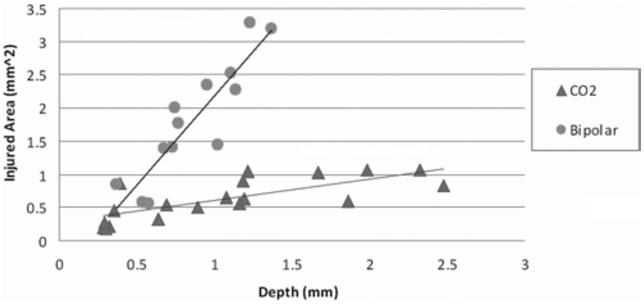

Fig. 8. Line graph demonstrating the relationship of the area of tissue affected compared with depth for laser and bipolar cautery application to the cortex. Given the high absorption of the CO_2 laser, a smaller area of tissue is affected as deeper incisions are made.

Conclusions

The PBF system with a handheld guide was easy

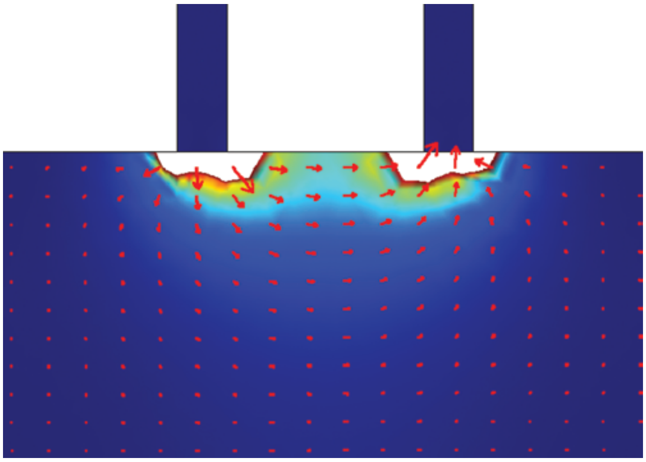

Fig. 9. Electric energy density *(color surface plot)* and electric field lines *(red arrows)* are shown for a simple 2D model of the electric field distribution for a bipolar cautery device when it is first applied to tissue. The probe contacts are assumed to be perfect electrical conductors, while the target tissue is modeled as a homogeneous dielectric. Note that the electric energy density penetrates the tissue to a depth comparable to the distance between the probe contacts, and is not limited to the surface of the tissue.

to use and able to precisely direct the CO_2 laser during normal operation of the neurosurgical microscope. The ability to both cut and coagulate with a single instrument, without need for manipulation of the underlying or surrounding tissue, and with minimal thermal effects on adjacent tissue, suggests CO_2 laser energy as delivered through this innovative flexible fiber assembly could be highly valuable during resections in eloquent areas and when near critical structures. The flexible fiber may also provide opportunities for application of the CO_2 laser in neuroendoscopy. One limitation of the high water absorption of the CO_2 laser is that it requires a dry operative field and is unable to penetrate through CSF. Further studies are warranted to follow tissue healing and neuronal survival after laser incisions, and to explore endoscopic functionality.

Disclosure

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