CO₂ Laser Fascia to Dura Soldering for Pig Dural Defect Reconstruction

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ABSTRACT

Background and objectives: The purposes of this study were to demonstrate that laser soldering is safe and effective for tissue bonding in dural reconstruction and to compare this new reconstruction technique to an established one. **Study design:** A temperature-controlled fiberoptic CO₂ laser system or fibrin glue were used for in vitro dural defect reconstruction in two groups of pigs. The CO₂ laser technique was also used for dural reconstruction in live pigs. **Results:** The burst pressure of the reconstructed dura by the laser system was significantly higher than that of fibrin glue (mean pressure 258.5 ± 117.3 cm H₂O and 76.8 ± 47.2 cm H₂O, respectively). There were no postoperative complications and no signs of thermal damage to the dura, fascia, or underlying tissue on histological analysis following the in vivo CO₂ laser experiments. **Conclusions:** Temperature-controlled laser soldering is an effective technique for dural repair. It creates a strong tissue bonding with no thermal damage to the tissue. The burst pressure of the reconstructed dura done with laser soldering is significantly higher than that of fibrin glue.

KEYWORDS: Anterior skull base, reconstruction, dura, CO₂

Dural defects may be caused by trauma, excision of skull base tumors, or iatrogenic complication of sinonasal surgery. Dural reconstruction is usually performed with fascia to form a watertight seal.¹ The aim of reconstruction is to provide a

barrier between the contaminated sinonasal space and the sterile subdural compartment. The dura must be tightly sealed so that it will support the instantaneous cerebrospinal fluid (CSF) pressure and withstand considerable shearing forces during

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the postoperative period. Dura to fascia bonding is ordinarily achieved with sutures and fibrin glue. Suturing, however, is not watertight, and CSF leakage through gaps between the sutures and through the needle holes is not uncommon. Old age, radiation therapy, and high-pressure hydrocephalus^{2,3} are risk factors for reconstruction failure when using this approach.

Laser soldering is an alternative approach for tissue bonding. This technique is based on applying some soldering material (such as albumin) onto the approximated edges of the cut and heating the solder and the underlying tissues by a laser beam. Laser soldering does not involve a foreign body (i.e., sutures, clips, staples, or synthetic glues) and offers some advantages over standard techniques: (1) it provides a watertight seal; (2) the wound healing process is faster;⁴ (3) there is potentially little scar formation;^{4,5} and (4) laser bonding can be undertaken endoscopically when sutures are not feasible. Researchers have studied laser bonding of numerous types of tissues for many years, but the method has not yet been widely accepted by surgeons.

The literature contains many reports describing laser soldering of different types of tissues.^{4,6-9} In our experiments we used a CO₂ laser which has a shallow tissue penetration depth because its energy is highly absorbed by water.¹⁰ Precise temperature control is a crucial issue in laser bonding: optimal soldering temperature can be maintained for preventing thermal damage to the bonded tissues and the underlying layers. We used an infrared computerized feedback system in our current experiments to maintain the surface temperature within a narrow range of $65 \pm 3^\circ\text{C}$.⁹

Two earlier studies discussed the use of laser bonding for dural reconstruction. One used a diode laser to close dural cuts in rats and reported desiccation of brain tissue.¹¹ The lack of temperature control or deep penetration of diode laser radiation into the tissue might have caused the thermal damage. The other study used a diode laser to close dural defects in the brainstem of dogs: most of the animals suffered postoperative CSF leakage.¹² These studies did not prove laser soldering to be

advantageous over standard dural closure techniques. The purpose of this report is to compare laser soldering and conventional fibrin glue repair in dural reconstruction of pigs in vitro and in vivo.

MATERIALS AND METHODS

Laser Soldering System

The laser soldering system we used has been described in detail elsewhere.^{4,13} Briefly, the system is based on a CO₂ laser, an infrared (IR) detector, two IR transmitting fibers, and a personal computer (PC). The CO₂ laser energy is transferred to the tissue through the first "power" fiber and heats the albumin and tissue surface. The warm tissue emits infrared energy which is transferred to the IR detector through the second "sensor" fiber. A computer program adjusts the laser output to maintain a constant surface temperature of $65 \pm 3^\circ\text{C}$. For the current experiments, we used a sealed-off CO₂ laser (Sharplan 40C, Lumenis, Yokneam, Israel) with an average laser power of 0.7 W. The solder was aqueous 47% bovine albumin (Sigma Chemical Co., St. Louis, MO). The albumin surface ($\sim 20 \mu\text{m}$) was heated by the laser soldering system and heat propagation into the tissue was caused by conduction.

In Vitro Laser Dural Repair (Pig Corpses)

Juvenile pigs that died of natural causes in the breeding farm were used for the in vitro experiments (The Institute of Animal Research (IAR), Kibbutz Lahav, Israel). The corpses were collected a short time after death and cooled to 4°C until the surgical procedure. A wide craniotomy of the superior aspect of the skull was performed and a circular 8-mm wide dural patch overlying the parietal lobe was excised. The fascia covering the longissimus et lumborum muscle on the back of the animal was used for reconstruction. A circular 15-mm wide

fascial patch was inserted in a subdural manner to reconstruct the defect. An overlap area of dura and fascia was created as the fascial patch was larger than the dural defect. The albumin solder was applied over the dura-fascia junction line and heated to $65 \pm 3^\circ\text{C}$ under microscopic magnification. These temperature values had already been studied in other tissues and were found to provide optimal strength without causing thermal damage.⁸ The tissue was then allowed to cool back to room temperature for 5 minutes after which a wide dural patch containing the soldered area in the middle was excised. The dura was meticulously separated from the arachnoid and immediately taken for burst pressure measurement using the system described below.

In Vitro Fibrin Glue Dural Repair (Pig Corpses)

Matched animals and the same surgical procedures used for laser dural repair were used for the fibrin glue experiments. After the fascia was inserted, fibrin glue (Quixil[®], MediMOP, Raanana, Israel) was spread over the fascia-dura junction line and allowed to dry for 10 minutes. A wide dural patch

that included the reconstructed area was then excised and taken for burst pressure measurement in the same system used for the laser soldering experiments (described below).

Burst Pressure Measuring System

A burst pressure measuring system was designed by us to determine the burst pressure of the reconstructed dura (Fig. 1). After dural excision, it was secured to a cylindrical tissue-holding device, which was custom-made for this purpose. The holding device was connected through a fluid pipe filled with saline to a piston which was pressed by a computerized load-measuring device (Instron, model 4502, Buckinghamshire, UK). When operated, the measuring device pushed the piston down causing fluid flow into the tissue holder. The system pressure was continuously measured by a pressure sensor, which was also connected to the fluid pipe. At a certain pressure, the adhesion at the dura-fascia junction line was disconnected and fluid leak caused rapid decrease in fluid pressure. The highest pressure achieved was defined as the burst pressure of the reconstructed dura.

Figure 1 The burst pressure measuring system. After dural excision, the system is secured to a cylindrical tissue-holding device, which was custom-made for this purpose. The holding device is connected through a fluid pipe to a piston which is pressed by a computerized load-measuring device (Instron, model 4502, Buckinghamshire, UK). When operated, the measuring device pushes the piston down, causing fluid to flow into the tissue holder. The system pressure was continuously measured by a pressure sensor, which was also connected to the fluid pipe.

Laser Soldering of Fascia to Dura — in Vivo Studies on Farm Pigs

Upon completion of the in vitro soldering experiments, the soldering model was implemented in live pigs. All procedures were in accordance to protocols approved by the Animal Care and Use Committee of Tel Aviv University. Sterilized equipment was used for the surgical procedure. Five pigs, each weighing about 12 kg, were used for the in vivo experiments (delivered by the IAR). Rocephin (ceftriaxone 50 mg/kg once a day) was given perioperatively for 2 days. Anesthesia was achieved by intravenous injection of pentobarbital 30 mg/kg. A small craniotomy over the parietal lobe was performed. Dural excision and reconstruction were performed in the same manner as for the in vitro laser soldering experiments. Dural closure was achieved by laser soldering of a single fascial layer inserted in a subdural plane (Fig. 2). After soldering, the excised craniotomy bone was put back in place and the skin incisions were closed. The animals were observed in the IAR for 10 days, with daily monitoring of food intake, behavior, and neurological status. At the end of the observation period, they were again anesthetized, the cra-

Figure 2 In vivo experiments. An 8-mm wide dural patch was excised through a small craniotomy (thick arrow, craniotomy border; thin arrow, brain tissue underlying the dura). A longissimus et lumborum fascial patch was inserted between the dura and brain tissue and albumin was applied over the fascia and heated by the laser system.

niotomy was reopened and enlarged and the soldered area was observed under microscope for CSF leak. En bloc excision of the soldered area with its underlying brain tissue was performed and the tissue was taken for histological analysis. The animal was then sacrificed by intracardiac injection of pentobarbital.

RESULTS

In Vitro Dural Reconstruction with Laser and Fibrin Glue

A total of 20 pig corpses were used in the in vitro experiments. The burst pressure values for dural reconstruction with laser soldering and fibrin glue bonding are presented in Figure 3. The mean burst pressure for the laser dura to fascia soldering group ($n = 10$) was 258.5 ± 117.3 cm H₂O (range 104 to 478). The mean burst pressure of the fibrin glue group (excluding one reconstruction failure) was 76.8 ± 47.2 cm H₂O (range 18 to 161). The difference in burst pressure between the two groups was highly significant in favor of the laser technique ($p = 0.0004$). Watertight bonding had been achieved in 9 out of the 10 animals in the fibrin group, while saline started leaking from the dura-fascia junction line before pressure could build up in one animal. This animal was considered as a failure and was not included in the statistical analysis. Thus the success rate of fibrin glue reconstruction was 90%.

In Vivo Dural Reconstruction with Laser Soldering

All five animals were observed for 10 days following laser dural reconstruction. The surgical wound healed well without CSF collection. All the animals gained weight as expected and no neurological signs or symptoms were observed. At the second craniotomy, the soldered area was tightly adhered and the

Figure 3 In vitro burst pressure measurements. The 20 animals were divided equally into two groups, one in which the laser soldering system was used for dural reconstruction and the other in which fibrin glue was used. Laser soldering yielded mean burst pressure of 258.5cm H₂O (solid line), significantly higher than fibrin glue (dotted line) which resulted in mean burst pressure of 76.8cm H₂O ($p=0.0004$).

tissue could not be separated by manipulation. Histological analysis showed fibroblast infiltration of the longissimus et lumborum fascia, with no signs of necrosis. The outer surface of the fascia and the dura-fascia junction contained inflammatory infiltrate. The dura-fascia interface was sealed. The arachnoid and pia mater showed no architectural changes or signs of damage, except for some mild recent bleeding. The brain tissue had normal appearance, with no signs of bleeding or thermal damage. The neurons and glial cells had normal histological features.

DISCUSSION

Dural reconstruction after craniotomy for trauma or tumor resection traditionally has been performed by means of sutures and fibrin glue. The use of these materials carries the risk of local inflammation and CSF leak. Laser soldering offers an alternative method that can generate a water-tight seal as well as achieve faster healing. The

mechanism of laser tissue bonding is not well defined, although a denaturation-renaturation process seems to produce the bonding effect.^{14,15} As such, the basic structure that interacts to create the tissue adhesion would, therefore, be protein, and fascia seems to be a natural choice for dural reconstruction since it is rich in collagen. Our temperature-controlled laser soldering system had been applied on various types of tissues in the past.⁷⁻⁹ In the current experiments, we used a CO₂ laser as the heating source because its radiation is highly absorbed in water and therefore has a shallow penetration depth (~20 μ m). The heat is propagated deep into the tissue by conduction. The temperature control of the tissue surface prevents overheating and, alternatively, insufficient heating of the soldered tissue, thus providing the tissue protein optimal conditions for the renaturation-denaturation process.

Foyt et al¹¹ used diode laser soldering for the closure of dural cuts in Lewis rats. The authors found dura soldering to be superior to conventional suturing, yielding a mean leak pressure of 26 mm Hg for soldering and 9.4 mm Hg

for suturing. Thermal damage to the underlying brain tissue was detected on histological analysis, and it might have been caused by the deep penetration depth of the diode laser energy or the lack of temperature control. Hadley and associates¹² compared CO₂ laser, suturing, and fibrin glue for dural defect reconstruction in dogs and reported that fibrin glue resulted in a stronger bond than laser soldering or sutures. Laser soldering was associated with CSF leak in most animals in this study.

We chose a temperature of 65°C because a strong bond had been achieved for other types of tissues at this temperature⁷⁻⁹ and because a major protein component of both the dura and the fascia is collagen, which is denatured at this temperature. The burst pressure of laser soldering is presented in Figure 2. This technique provided strong and watertight bonding, and even the lowest value (104 cm H₂O) was sufficient to withstand a sudden increase in intracranial pressure during coughing or Valsalva's maneuver.

Dural reconstruction is conventionally performed with sutures and fibrin glue by many surgeons.¹⁶⁻¹⁸ Endoscopic excision of skull base tumors and endoscopic repair of a CSF leak is becoming an alternative approach to open procedures in selected cases, and dural reconstruction is a major surgical issue in those instances. Since sutures are not feasible in endoscopic surgery, fibrin glue emerges as the only tissue-bonding material to date. Various reports about endoscopic dural reconstruction described success rates of around 90%,^{3,19,20} which leaves 1 in 10 patients with insufficient closure of the defect.

Our review of the literature yielded no previous reports of burst pressure measurements of dural reconstruction using fibrin glue. The purpose of the current study was to compare our novel dural closure model by CO₂ laser to an established technique. Although generally strong, fibrin glue and a single fascial layer produced successful bonding in 9 out of 10 instances, equivalent to the success rate of endoscopic dural reconstruction, which is also done with the use of fibrin glue but without

sutures. The burst pressure was relatively low in an additional two animals (18 cm H₂O and 23 cm H₂O), which might cause CSF leak if intracranial pressure is elevated due to a Valsalva's maneuver or cough. Laser soldering produced both a significantly stronger bonding than fibrin glue ($p=0.0004$) and a watertight bond in all experiments and so seems to be a reliable and safe option for repair of small dural defects. Further studies are needed to compare fibrin glue and laser soldering in the reconstruction of larger dural defects. In addition, evaluation of strength and water tightness of each technique in double-layered fascial reconstruction is warranted.

The standard deviation was high for both laser soldering and fibrin glue repair. Burst pressure measurement of the reconstructed dural defect is dependent on the weakest point along the soldered line. Even if there is a strong bond along most of the junction line, one small area of weakness will cause the entire reconstruction to give way and so it determines the burst pressure of the whole tissue. Unlike fibrin glue, areas of weak bonding could form when there are less-than-optimal soldering conditions (i.e., not enough heating by conduction of the deep layers of the albumin, fascia, or dura) when laser soldering is used. Areas of weak bonding can also form when fibrin glue is used if the two components of the glue are not mixed effectively at certain points along the dura-fascia junction line. Histological analysis of the surgical specimen of live pigs that were observed for 10 days after laser surgery showed bonding of the fascia to the dura without necrosis or excessive inflammation. The pia mater and the underlying brain tissue were intact and showed no signs of thermal damage. The neurons, which are highly sensitive to damage and do not regenerate, appeared normal. No glial cell changes were observed. This normal appearance of the brain tissue supports the assumption that the use of the temperature-controlled laser system is safe and that the controlled CO₂ laser energy will not penetrate structures beyond the intended soldered area.

CONCLUSIONS

We developed a novel technique for dural reconstruction that includes a temperature-controlled fiberoptic laser soldering system. The surface temperature was precisely controlled by the system during soldering, thus producing both optimal temperature for soldering and protection from thermal damage. The mean burst pressure of the reconstructed dura was 258.5 cm H₂O, which is much higher than the physiological CSF pressure (up to 20 cm H₂O). Although generally strong, the reconstruction with fibrin glue had significantly lower burst pressure compared with laser soldering (mean 76.8 cm H₂O, $p = 0.0004$) and was successful in only 90% of cases. Laser soldering dural reconstruction in five live animals was not associated with any complications, and histological analysis did not show any sign of thermal damage to the successfully soldered tissue or to the underlying brain. Our results demonstrated the potential of the temperature-controlled CO₂ laser system in dural reconstruction as a safe and reliable technique.

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