Dural Defect Repair with Fascia by a CO₂ Laser System in a Porcine Model

Boaz Forer; Tamar Vasilyev; Tamar Brosh; Naam Kariv; Leonor Leider Trejo; Ziv Gil; Abraham Katzir; Dan M. Fliss

Laser soldering is an alternative technique for tissue bonding. Albumin is applied onto the approximated edges of the tissue and is heated by a laser beam. This technique does not involve a foreign body such as suture. The potential advantages of laser compared to conventional suturing are that (1) it can be applied endoscopically, (2) it generates a watertight bond, (3) the time to wound healing might be shorter, and (4) there is relatively little scar formation. The mechanism of laser soldering is not fully understood, although it appears to be a heating-induced protein denaturation-renaturation process.¹

Review of the literature revealed only two reports on dural reconstruction using lasers. In the first report, a diode laser with albumin solder was used to close dural cuts in rats.² No temperature control was applied, and the soldering resulted in thermal damage to the underlying brain tissue. The second report described brainstem dural defect reconstruction in dogs,³ which was not watertight in six of seven animals.

Our group has carried out experimental studies on laser soldering of skin, urinary bladder, blood vessels, and cornea.¹⁻⁴ The results of these experiments showed that laser soldering resulted in good closure, less inflammatory reaction, and very little scarring.⁷⁻⁸ Temperature control is essential to achieve optimal soldering results and to avoid thermal damage to the underlying tissue. Based on these experiments, we created a model for the reconstruction of a dural defect with fascia using a CO₂ laser system. Farm pigs were chosen for this study because their brain size and dural thickness were suitable for surgical manipulation.

The purpose of this study was to create a model for dural reconstruction using a temperature-controlled CO₂ laser system.

MATERIALS AND METHODS

Laser Soldering System

The Applied Physics group at the Tel Aviv University (Israel) developed a unique temperature-controlled CO₂ laser system. The main idea is to apply biologic solder (i.e., albumin) on the approximated edges of a cut and heat the albumin and underlying tissue to a narrow temperature range (65 ± 3°C). The CO₂ laser was chosen because its radiation is highly absorbed by water and hence does not penetrate deeply into the tissue.¹⁶
The system is based on a CO₂ laser, an infrared detector (IRD), two silver halide fibers, and a personal computer (PC). One of the fibers delivers energy from the CO₂ laser to the tissue and heats it. The warm tissue emits infrared radiation, which is transferred through a second fiber to an IR detector. A computer program continuously adjusts the laser energy according to the IR fiber input to maintain a constant temperature on the tissue surface.

The system is based on a CO₂ laser, an infrared detector (IRD), two silver halide fibers, and a personal computer (Fig. 1). One of the fibers delivers energy from the CO₂ laser to the tissue and heats it. The warm tissue emits infrared radiation, which is transferred through a second fiber to an IRD. A computer program continuously adjusts the laser output according to the IRD input to maintain a constant temperature on the tissue surface. Aqueous 47% bovine albumin (Sigma Chemical, St. Louis, MO, U.S.A.) was used as a solder in all experiments.

**Animal Model and Surgical Procedure: In Vitro Experiments**

For this part of the study, we used juvenile farm pigs (7–19 kg) that died of natural causes in the Institute of Animal Research, Kibutz Lahav, Israel. A circular 8 mm dural patch located approximately 10 mm off the midline and midway between the anterior and posterior ends of the brain was excised through a wide craniotomy. Reconstruction was done with the fascia investing the longissimus et lumborum muscle (located under the skin on the animal’s back). This fascia is tightly adhered to the muscle fibers on its inner “muscular” side. Its outer “fatty” side facing the skin, however, is loose and covered by a thin fat layer. The fascia was separated from the muscle and excised. A circular 15 mm fascial patch was inserted between the dura and brain tissue, resulting in an overlapping area. The albumin solder was spread over the dura-fascia junction line and the tissue was heated by the laser system to 65 ± 3°C. At the end of the procedure, a wide dural patch with the soldered area in the middle was excised and taken for burst pressure measurement, using the system described below.

**Burst Pressure Measurements**

The dural patch was attached to the top of a holding device shaped like a drinking glass, which was custom-made for this purpose. Fluid was driven into the holding device by a computerized system (Instron, model 4502, Buckinghamshire, U.K.) and the pressure inside the device was continuously measured by a pressure detector. With increasing pressure, the weakest point of the soldered dura-fascia line eventually disconnected, resulting in fluid leak though the opening and a rapid drop in pressure. The burst pressure of the reconstructed dura was defined as the peak pressure (Fig. 2).

**In Vivo Experiments**

In vivo experiments on five live pigs weighing 12 kg each were carried out according to the regulations of the animal care and use committee at Tel Aviv University. General anesthesia was achieved with pentobarbital 30 mg/kg (Nembutal). Cetriaxone (Teva, Petah Tikva, Israel) 50 mg/kg once a day was given perioperatively for 2 days. The surgical procedures were performed using sterile equipment. A small circular craniotomy was performed over the parietal lobe. Dural excision and reconstruction were done at the same place and in the same manner as described for the in vitro model. Soldering was done under microscopic magnification. The circular craniotomy bone was secured back in place using bone cement. The animal was scheduled for euthanasia 10 days after surgery. Until then it was observed daily by the Institute of Animal Research staff who noted food intake, neurologic status, and wound condition. At the end of the observation period, the animal was anesthetized, the surgical wound was re-opened, and the soldered area was checked for CSF leak. En bloc excision of the dura containing the soldered area with the underlying brain was then performed. The specimen was fixated using 4% formaldehyde solution and stained by hematoxylin-eosin. The anesthetized animal was killed with an intracardiac injection of pentobarbital.

**RESULTS**

**Burst Pressure Measurements: In Vitro Model**

We used 27 pig corpses divided into three groups: the first group consisted of nine pigs, which were operated on without the use of magnification (direct vision soldering [DVS]). The second group consisted of eight corpses, and soldering was done under microscopic magnification with the outer “fatty” side of the fascia facing the dura (microscopic fatty side soldering [MFSS]). In the third group, 10 animals were operated on under a microscope with the inner “muscular” side of the fascia facing the dura (microscopic muscular side soldering [MMSS]). Burst pressure measurements were carried out using the computerized system discussed earlier. The results are displayed in Table I. DVS produced the lowest burst pressure results (mean 120.1 ± 61.8 cm H₂O). MFSS yielded an intermediate bonding strength (mean 139.6 ± 51.7 cm H₂O). MMSS resulted in the highest burst pressure (mean 258.5 ± 117.3 cm H₂O), which was significantly higher than both DVS (P = .001) and MFSS (P = .008), and more than...
10 times higher than the physiologic intracranial pressure (approximately 20 cm H$_2$O).

**Dural Reconstruction: In Vivo Experiments**

The surgical procedure was done as described above in five live animals. When the craniotomy was reopened after a 10-day observation period, the soldered area was seen to be covered by granulation tissue (Fig. 3). No CSF leak was detected. The dura-to-fascia bonding was strong and the soldered area could not be separated by manipulation (i.e., prodding by a blunt instrument). To verify a watertight seal, a lumbar puncture was then performed and blue dye was injected through the lumbar puncture needle. The CSF pressure was raised to 30 cm H$_2$O by saline injection through the needle and maintained for 30 minutes. During this time, the blue dye was visible under the dura and no leak was detected. The soldered area and underlying brain tissue were resected en bloc at the end of the experiment.

The microscopic appearance of the soldered area is presented in Figure 4.

<table>
<thead>
<tr>
<th>Serial No.</th>
<th>Animal Weight, kg</th>
<th>Burst Pressure, cm H$_2$O</th>
<th>Serial No.</th>
<th>Animal Weight, kg</th>
<th>Burst Pressure, cm H$_2$O</th>
<th>Serial No.</th>
<th>Animal Weight, kg</th>
<th>Burst Pressure, cm H$_2$O</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7</td>
<td>160</td>
<td>10</td>
<td>7</td>
<td>50</td>
<td>18</td>
<td>7.5</td>
<td>192</td>
</tr>
<tr>
<td>2</td>
<td>11.5</td>
<td>114</td>
<td>11</td>
<td>7</td>
<td>113</td>
<td>19</td>
<td>7.5</td>
<td>165</td>
</tr>
<tr>
<td>3</td>
<td>19.5</td>
<td>57</td>
<td>12</td>
<td>7</td>
<td>175</td>
<td>20</td>
<td>9</td>
<td>104</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>55</td>
<td>13</td>
<td>7</td>
<td>164</td>
<td>21</td>
<td>10.5</td>
<td>377</td>
</tr>
<tr>
<td>5</td>
<td>7</td>
<td>192</td>
<td>14</td>
<td>7</td>
<td>116</td>
<td>22</td>
<td>9</td>
<td>258</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>159</td>
<td>15</td>
<td>12</td>
<td>131</td>
<td>23</td>
<td>9</td>
<td>271</td>
</tr>
<tr>
<td>7</td>
<td>13</td>
<td>193</td>
<td>16</td>
<td>8</td>
<td>226</td>
<td>24</td>
<td>7</td>
<td>122</td>
</tr>
<tr>
<td>8</td>
<td>13</td>
<td>124</td>
<td>17</td>
<td>7</td>
<td>142</td>
<td>25</td>
<td>9</td>
<td>291</td>
</tr>
<tr>
<td>9</td>
<td>13</td>
<td>27</td>
<td>27</td>
<td>7</td>
<td>478</td>
<td>26</td>
<td>7</td>
<td>327</td>
</tr>
</tbody>
</table>

Mean pressure 120.1 ± 61.8

Mean pressure 139.6 ± 51.7

Mean pressure 258.5 ± 117.3

---

**Fig. 3.** After a 10-day observation period, the surgical wound was re-opened. A wide craniotomy was performed. Blue dye was injected intrathecally and the CSF pressure was raised to 30 cm H$_2$O for 30 minutes. Bulging of the soldered area due to elevated CSF pressure can be seen, without CSF leak. Black arrow is pointed at the margin of the previous small craniotomy. The dura and soldered area at this site were covered by granulation tissue. White arrow is pointed at the margin of the wide craniotomy.

**Fig. 4.** Histologic appearance of the soldered area after 10 days. The fascia (F) and dura (D) show mild fibroblast infiltration with no signs of necrosis. On the inner “fatty” side of the fascia fat cells can be seen (arrows). The outer surface of the dura and fascia shows hyaline material representing the albumin layer (A) and lymphocyte infiltration. The dura-fascia junction line is tightly adhered. The arachnoid, pia, and brain tissue (B) show no signs of thermal damage. The neurons and glial cells appear normal.
DISCUSSION
Repair of dura following trauma or tumor extirpation is conventionally done by synthetic suture materials that can cause local inflammatory reaction and slow the healing process. Moreover, the reconstruction is not watertight and fluid can leak in-between the sutures themselves or through the suture holes. Laser heating offers an alternative technique that could generate a watertight seal and good tensile strength. The absence of sutures allows a faster healing process without foreign body reaction.

Two previous studies described the use of laser soldering for dural reconstruction. The first described the use of diode laser soldering for dural repair in Lewis rats. The results showed that soldering yielded better bonding strength than sutures (mean leak pressure of 34 cm H2O vs. 12.3 cm H2O, respectively). Thermal damage to brain tissue was observed on histologic examination. The burst pressure value of the soldered tissue was much lower than our results. Deep penetration of diode laser radiation compared to CO2 wavelength and the lack of temperature control may be responsible for the brain tissue damage and weaker bond. In the second report, CO2 laser without temperature control was used for dural reconstruction in dogs. The authors observed CSF leakage immediately after the procedure in most animals. They also found that fibrin glue supported more than 50 cm H2O of CSF pressure, emerging as being superior to both laser and sutures. In our experiments, a much higher bonding strength (mean, 258.5 ± 117.3 cm H2O) was observed using laser soldering. The lack of precise temperature control might be the reason for the weak and not watertight bond in this study.

In our study, we have successfully bonded fascia to dura both in an in vitro setting and in live animals and showed that no thermal damage was inflicted on the soldered tissue or the underlying brain. This report is the first successful attempt to reconstruct a dural defect with fascia by a CO2 laser. The rationale for the use of a CO2 laser is its high absorption rate in water. The laser energy heats only the top layer (roughly 20 μm) and does not penetrate deep into the tissue. We chose a porcine model because the pig brain is relatively large, thus providing a wide surgical field for dural excision and reconstruction, and its dura and the fascia are relatively thick compared to those of smaller animals (i.e., rats or rabbit), making them easier to manipulate. We decided to use a patch that was larger than the hole and to bond the fascia to the dura in an end-to-side fashion because placement of a fascial patch that will exactly match the hole is technically difficult and had reportedly produced inferior bonding results in preliminary experiments.

The mechanism of tissue soldering is not fully understood, although protein denaturation-renaturation seems to be the biologic process involved. The use of fascia as the reconstruction material would appear to be a “natural” choice, since it is protein rich and is the tissue of choice for dural reconstruction in humans by many authors. The use of the muscular side of the fascia, which is rich in protein and has an irregular, large surface area, proved to produce significantly stronger bond than the fatty side of the same fascia. This result supports the assumption that soldering involves protein-based bonding.

We believe that the current report is the first to compare soldering with and without magnification. The use of an operating microscope for magnification significantly improved our soldering results by enabling the surgeon to see tissue’s reaction to heating (i.e., shrinkage and movement) under the albumin solder, which is very difficult to see without magnification. In our soldering experiments, the albumin layer was sometimes too thick or the laser fiber movement too fast, which resulted in heating of the superficial albumin layer but insufficient heat conduction into the tissue and a weaker bond. When this problem was observed under the microscope, the procedure was stopped and the necessary adjustments made so that optimal heating was achieved at every point along the dura-fascia junction line.

For soldering of the muscular side (MMSS), the mean burst pressure (258.5 cm H2O) was more than 10 times the physiologic CSF pressure (approximately 20 cm H2O). These encouraging results support the assumption that laser soldering of fascia to dura can withstand CSF pressure without the risk of leak. Even the lowest value that we recorded for MMSS (104 cm H2O) was sufficient for all practical applications.

In the in vivo experiments, the animals were observed for 10 days and no neurologic or surgical complications (e.g., CSF leak) were noted. Histologic examination of the surgical specimen showed a watertight seal with no evidence of brain tissue damage. Furthermore, bonding of the fascia and dura was complete, without necrosis or excessive inflammation.

Our laser system has the potential to be used in endoscopic surgery; hence, laser soldering offers an alternative to fibrin glue for endoscopic dural reconstruction. Moreover, soldering can be done in deep and narrow areas of the skull base (e.g., sphenoid and sellar region) were suture placement is difficult, therefore providing the surgeon with another tissue bonding technique for dural reconstruction in those areas.

CONCLUSIONS
Temperature-controlled laser soldering is a reliable technique for the reconstruction of dural defects. It is easy to apply and creates a watertight bond and better wound healing. Laser tissue soldering might replace conventional techniques in dural reconstruction in difficult to reach skull base areas and in endoscopic surgery.

Acknowledgments
Esther Eshkol is thanked for editorial assistance.

BIBLIOGRAPHY


