Waterjet dissection in pediatric cranioplasty

Technical note

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Object. Waterjet dissection has been shown to separate tissues of different resistance, with preservation of blood vessels. In cranioplasty, separation of subcutaneous tissue and dura mater is often difficult to achieve because the various tissue layers strongly adhere to each other after decompressive craniotomy. In the present study, the potential advantages and drawbacks of the waterjet technique in cranioplasty after craniectomy and duraplasty are addressed.

Methods. The waterjet effect on fresh human cadaveric dura mater specimens as well as on several dural repair patches was tested in vitro under standardized conditions, with waterjet pressures up to 80 bar. Subsequently, 8 pediatric patients (5 boys, 3 girls; mean age 9.9 years, range 1.2–16.7 years) who had been subjected to decompressive craniectomy (7 with duraplasty including bovine pericardium as a dural substitute, 1 without duraplasty in congenital craniostenosis) underwent waterjet cranioplasty. The waterjet was used to separate the galea and the dura mater. The technique was applied tangentially between the dura and the galea, with different pressure levels up to 50 bar.

Results. In vitro, fresh cadaveric human dura mater as well as 2 different dural repair substitutes showed a very high resistance to waterjet dissection up to 80 bar. The human dura and the various substitutes were dissected only after long-lasting exposure to the waterjet. Human dura was perforated at pressures of 60 bar and higher. Bovine pericardium dural substitute was perforated at pressures of 55 bar and higher. Artificial nonabsorbable polyesterurethane dural substitute was dissected at pressures of 60 bar and higher. In the clinical setting, the waterjet was able to separate galea and dura with minimal bleeding. No blood transfusion was required. Dissection of scarred tissue was possible by a waterjet of 40 bar pressure. Tissue layers were stretched and separated by the waterjet dissection, and a very reliable hemostasis resulted. This resulted in an effective reduction of bleeding, with < 60 ml blood loss in 7 of the 8 cases. Neither a dural tear nor a perforation of any duraplasty occurred during operative preparation. There were no operative or postoperative complications.

Conclusions. The experimental and clinical data show that waterjet separation of dura mater, dural substitute, and galea can be performed with a high level of safety to avoid dural tears. The waterjet dissection stretches tissue layers, which results in a reliable hemostasis effect. This potentially results in an effective reduction of surgical blood loss, which should be the focus of further studies. (DOI: 10.3171/2009.10.PEDS09308)

Key Words • Erbejet 2 • waterjet dissection • hydrojet dissection • cranioplasty • surgical technique • hemostasis

Waterjet dissection is applicable to many surgical procedures. This alternative dissection technique offers precise tissue separation without thermal side effects, thus preserving vessels and nerves. Reduced blood loss and less damage to tissue and neural structures might result, which potentially could improve the patient’s postoperative clinical outcome. So far, use of the waterjet scalpel has been established in liver surgery, urological surgery, neurosurgery, and others.16,18,22,28,36,32,34,36,37,39 Each surgical discipline uses its own particular application technique. In neurosurgical applications, experimental studies have underlined the safety and potential advantages of waterjet dissection.27,29,31,41,42 Rather low waterjet pressures (up to 12 bar) are sufficient for brain tissue and brain tumor dissection.28,32,34,37 In addition to this conventional use, the waterjet might offer further options. Abrasive waterjet techniques in reconstructive surgery, such as fatty tissue dissection for liposuction, wound cleaning in burn patients, or debridement of problematic wounds, already exist.3,5,9–11,15,21,22,39 Another waterjet effect was observed in gastric endoscopy. This “expansion” effect causes a

Abbreviation used in this paper: Hb = hemoglobin.
submucosal fluid cushioning, which allows a separation of gastric mucosa from the gastric wall, optimizing endoscopic lesion resection.18,19,24,40

Cranioplasty is a very common neurosurgical procedure in adults and children, including infants. There are various indications for cranioplasty in pediatric neurosurgery.13,17,23,26,43 One large cohort consisted of children who had suffered a severe head injury and underwent decompressive craniectomy.1,2,8,20,25,35,38 Autologous or artificial reconstructive cranioplasty will be performed in most of these patients according to their rehabilitation protocol. Further indications arise from skull tumor resection or are encountered due to decompressive craniectomy in selected patients suffering from premature craniosenosis. After decompressive surgery, these skull defects result in scar tissue adherent to the dura mater or to the allogenic dural substitute.23,43 This carries the risk of CSF leakage or brain tissue damage during common sharp dissection techniques. Especially in pediatric neurosurgery, the amount of blood loss and the decrease in body temperature are essential factors for operative morbidity and outcome.4,6,7,12–14,17,26 Intensive use of diathermy to the skin may also induce wound healing disorders and infections. Therefore, minimally invasive operative preparation techniques are essential.

Methods

Study Design

In this study we experimentally investigated the effect of waterjet dissection on human dura mater and various dural substitutes. Based on the results, the technique was clinically applied in cranioplasty procedures. Special attention was given to the technique’s potential in separation of the tissue layers and preservation of the dural integrity.

Description of the Waterjet Device

Waterjet dissection procedures were performed with the new Erbejet 2 device (ERBE Elektromedizin GmbH; Fig. 1a). This system has been available since 2007 and was approved for use in human surgery by the regulatory authorities in Germany and in the US. The waterjet pressure is generated by a sterile, single-use, double-piston pump. The jet nozzle diameter of the standard applicator tip for neurosurgical application is 120 μm. The adjustable suction device is integrated into the nozzle. The pressure ranges from 1 to 80 bar (100–8000 kPa), with a volume flow of 1–55 ml/minute as a thin laminar liquid jet (Fig. 1b). The recommended separation medium is sterile physiological saline solution, although the separating medium can be freely selected via a conventional infusion container.42

Experimental Application

Investigations consisted of a laboratory test battery for which fresh human cadaveric dura mater, bovine pericardium dural repair patch (Dura-Guard, Synovis Surgical Innovations), and nonabsorbable polyesterurethane patch for dura mater substitution (Neuro-Patch, Aesculap AG) were used, with tests involving pressures from 10 to 80 bar. In brief, the waterjet was sequentially applied with pressure levels of 40, 50, 55, 60, 70, and 80 bar to the specimen under standardized conditions. The standard 120-μm applicator nozzle (Fig. 1b) was assembled in a specially developed device that allowed presetting the waterjet nozzle-to-target distance and cutting velocity (Fig. 1a [left side], 1c). The distance from nozzle tip to the dura mater was 2 mm, angle 90°, and cutting velocity 0.3 cm/second (Fig. 1c). Additionally, the waterjet was directly applied in the orthogonal direction of the nozzle tip to the specimens for 1 minute. The impact of the waterjet on the dura and surrogate materials was microscopically analyzed, video recordings were made, and photo documentation was performed (Fig. 1d, Video 1).

**Fig. 1.** Setting for experimental waterjet testing. a: The linearity device for standardized experimental waterjet application (left) and the waterjet dissection device Erbejet 2 (right) are shown. b: Standard 120-μm applicator nozzle emitting a thin laminar jet. c: Linearity device with the assembled standard applicator in orthogonal direction (distance from nozzle tip to dural repair patch 5 mm, cutting velocity 0.3 mm/second). d: Waterjet dissection results on bovine pericardium dural repair patch (Dura-Guard). Up to 80 bar pressure level, no dissection was observed.
Clinical Application

Eight children underwent operation for reconstructive cranioplasty with application of the waterjet dissector. Five children underwent decompressive craniectomy for severe head injury; 4 of them had unilateral and 1 had bilateral decompression. Two children with generalized brain edema underwent unilateral decompression; 1 for brain swelling after a drowning accident, and the other because of toxic brain swelling in hepatic failure. In the last case, cranioplasty was performed when the patient was 14 years of age, after sagittal suture resection in early infancy for craniostenosis. Five patients were boys and 3 were girls. The average age of the total group was 9.9 years (range 1.2–16.7 years, Table 1). The waterjet was adjusted between 30 and 50 bar. The isotonic saline solution was preheated to normal body temperature to prevent the situs from cooling. The waterjet was applied for opening the wound and separating the skin from duraplasty or dura mater. The maximum waterjet pressure was 50 bar in an inclined application angle. Direct contact in a vertical direction to the dura was strictly avoided. The cutting effects were documented. The Hb value was measured pre- and postoperatively in the patient and in the suction fluid. Blood loss was assessed by the following formula:

\[
\text{Blood loss (dl)} = \text{Hb (g/L)} \times \text{total volume suction (L)} = g \text{ erythrocyte volume loss} = g \text{ erythrocyte/preoperative Hb (g/dl)}.
\]

This formula allows estimation of blood loss with regard to a dilution effect in up to 4.5 L of cutting medium. Postoperatively, a CT scan was performed. All children underwent follow-up examinations as a part of regular postoperative care.

Results

Experimental Studies

At up to 40 bar waterjet pressure with continuous longitudinal movements of 0.3 cm/second, no effects on the various specimens were observed. Thus, more detailed tests were done only after pressures of 40 bar or more had been applied to the various specimens.

Bovine Pericardium Dural Patch (Dura-Guard). Forty bar resulted in a superficial scratch of the bovine pericardium dural patch. At a 2-mm distance and with slow longitudinal movements of the nozzle (0.3 cm/second), higher pressures resulted in deeper scratches, but even at 80 bar the patch was not perforated (Fig. 1d, Table 2). With direct contact to the patch and a fixed nozzle position, no perforation of the patch was observed up to 50 bar. Above that threshold, a penetration of the patch occurred at 55 bar after 15 seconds, and progressively earlier with higher pressures.

Polyesterurethane Patch (Neuro-Patch). With a 2-mm distance and longitudinal movements, this patch demonstrated the highest resistance to waterjet dissection. No cutting and not even a scratch was observed, even at 80 bar (Table 2). With direct contact to the patch and a fixed nozzle position, a perforation was seen at 70 bar after 20 seconds and at 80 bar after 3 seconds.

Unfixed Fresh Human Cadaveric Dura Mater. At a 2-mm distance and with longitudinal movements, no effect was observed up to 55 bar. At 60 bar and higher, the waterjet inflicted scratches of increasing depth (Table 2). With direct contact to the patch and a fixed nozzle position, a perforation was observed at 60 bar after 11 seconds, and progressively earlier at higher pressures. In summary, the laboratory test revealed a reliable resistance of the various materials to waterjet perforation up to pressures of 50 bar.

Clinical Application

With regard to the experimental results, a waterjet pressure of 40 to 50 bar was selected for the clinical application. After sharp skin incision including reopening of the scar, the waterjet was applied for cutting of the subcutaneous layer and preparation of the craniectomy defect. Application of the waterjet to the wound edges resulted in immediate hemostasis (Fig. 2, Video 2).

Video 2. Clip showing waterjet application to a scarred wound. Application of the waterjet immediately stops the bleeding after skin incision; bloody wound edges were transformed to a white bloodless color. Hemostasis is achieved by expansion of the subcutaneous tissue by water edema and subsequent compression of the blood vessels. The waterjet protects the dura (upper part of the wound) while separating the skin from the dura. The scarred skin tissue can be dissected by the waterjet without damaging the dura. Click here to view with Windows Media Player.

This effect was most likely caused by water inflow and...
edema of the subcutaneous layer. Subsequently, the blood vessels were compressed, and hemostasis resulted without application of diathermy. This hemostasis lasted for several minutes, up to a maximum of 15 minutes. No rebleeding from the wound edges was observed, even after several minutes.

The preparation of large skull defects with a thin skin layer adherent to the dura mater, allogenic dura, or skull bone was easily accomplished with the waterjet. No injury to the dura or the dural patch occurred. However, we tried to avoid a direct waterjet dissection of the suture line between dura and any dural substitute because (with the exception of autologous material) the interface between the dura and the substitute is very fragile and can be disrupted with the waterjet, even with low pressures. Extremely scarred skin was only cut partially by the waterjet at 50 bar. Therefore, scissors were sometimes additionally used for cutting. The best effect was achieved at 50 bar waterjet pressure. The dural patch or dura was separated gently from the adherent skin by the waterjet (Fig. 3). Wound closure was easily achieved at the end of the procedure in all cases.

There were no surgery-related complications. The mean surgical time was 127.5 minutes (range 79–290 minutes bilaterally, Table 3). The use of up to 4.5 L of cutting

<table>
<thead>
<tr>
<th>Water Pressure (bar)</th>
<th>2-mm Application Distance</th>
<th>Effect After 1 Min</th>
</tr>
</thead>
<tbody>
<tr>
<td>bovine pericardium patch</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>superficial scratch</td>
<td>no perforation</td>
</tr>
<tr>
<td>50</td>
<td>superficial scratch</td>
<td>no perforation</td>
</tr>
<tr>
<td>55</td>
<td>superficial scratch</td>
<td>perforation after 15 sec</td>
</tr>
<tr>
<td>60</td>
<td>visible scratch</td>
<td>perforation after 10 sec</td>
</tr>
<tr>
<td>70</td>
<td>deep scratch</td>
<td>perforation after 1 sec</td>
</tr>
<tr>
<td>80</td>
<td>deep scratch</td>
<td>immediate perforation</td>
</tr>
<tr>
<td>polyesterurethane patch</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>no scratch</td>
<td>no perforation</td>
</tr>
<tr>
<td>50</td>
<td>no scratch</td>
<td>no perforation</td>
</tr>
<tr>
<td>55</td>
<td>no scratch</td>
<td>no perforation</td>
</tr>
<tr>
<td>60</td>
<td>no scratch</td>
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</tr>
<tr>
<td>70</td>
<td>no scratch</td>
<td>perforation after 20 sec</td>
</tr>
<tr>
<td>80</td>
<td>no scratch</td>
<td>perforation after 3 sec</td>
</tr>
<tr>
<td>unfixed human cadaveric dura mater</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
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<td>no perforation</td>
</tr>
<tr>
<td>50</td>
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</tr>
<tr>
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<tr>
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<td>perforation after 6 sec</td>
</tr>
<tr>
<td>80</td>
<td>visible scratch</td>
<td>perforation after 2 sec</td>
</tr>
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</table>

* The waterjet was applied at a 2-mm distance with a constant longitudinal movement velocity of 0.3 mm/second. Additionally, the waterjet was applied in a vertical direction, with direct contact of the nozzle tip to the dural specimen’s surface for 1 minute (effect in place). The first group of data gives the waterjet’s cutting effects on a bovine pericardium dural repair patch (Dura-Guard), the second group lists the cutting effects on a nonabsorbable polyesterurethane patch for dura mater substitution (Neuro-Patch), and the third group summarizes the results of experimental waterjet cutting of human cadaveric dura mater.
Waterjet dissection in pediatric cranioplasty

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Op Time (min)</th>
<th>Blood Loss (ml)</th>
<th>Postop Hb (g/dl)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>96</td>
<td>&lt;40</td>
<td>9.6</td>
</tr>
<tr>
<td>2</td>
<td>85</td>
<td>&lt;50</td>
<td>9.8</td>
</tr>
<tr>
<td>3</td>
<td>115</td>
<td>&lt;50</td>
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<tr>
<td>4</td>
<td>125</td>
<td>&lt;50</td>
<td>10.4</td>
</tr>
<tr>
<td>5</td>
<td>140</td>
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<td>&lt;60</td>
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</tr>
<tr>
<td>7</td>
<td>290 (bilat)</td>
<td>&lt;150</td>
<td>8.9</td>
</tr>
<tr>
<td>8</td>
<td>79</td>
<td>&lt;50</td>
<td>10.5</td>
</tr>
</tbody>
</table>

* Operating time (mean 127.5 minutes) and calculated blood loss (in milliliters). Postoperative Hb screening excluded the need for blood transfusion. The blood loss was estimated by the detection of Hb in the total suction fluid. The following formula was used for blood loss calculation: blood loss (dl) = Hb (g/L) suction × volume suction (L) = g erythrocyte volume loss = g erythrocyte/preoperative Hb (g/dl).

medium induced a distinct dilution of the suction fluid. With the aid of the Hb value in the total suction fluid, the blood loss was calculated. With the single exception of bilateral cranioplasty, all patients had an estimated blood loss of < 60 ml. Blood transfusion was not necessary in any case. The postoperative CT scan, obtained within the first 3 days, showed no complications: no epidural or subdural hemorrhages were found, and especially, no water or air inclusions were noted, which could indicate dural damage. Follow-up examinations demonstrated a fast healing process with no signs of infection. Up to a follow-up period of 22 months (range 2–22 months), no wound healing failure, infection, or rejection reaction of the autologous or artificial cranioplasty occurred.

**Discussion**

Waterjet dissection is an established technique for vessel and nerve preservation and tissue dissection. In the present study, the waterjet was used in pediatric cranioplasty. The results of this study suggest also an expansion and cushioning effect in human cranioplasty due to a subcutaneous edema, as shown in Fig. 4. Tissues such as skin and dura mater are precisely separated by expansion. Subcutaneous vessels are compressed by edema, and immediate hemostasis results. Due to these effects, the waterjet is able to separate tissue layers of different resistances. Separating the covering skin from materials used for duraplasty or from intact dura was shown to be easily accomplished. Additionally, extensively scarred tissue could be expanded and dissected. For this technique, the experimental and clinical aspects of the current study suggest a pressure of 40 to 50 bar, because no severe damage or cut-through penetration of the dura was observed at that intensity. Particularly in pediatric neurosurgery, a gentle and blood-saving surgical cutting technique will improve patients’ safety. Thus, our observations in the current study have to be considered for further evaluation. Before definite conclusions can be drawn, however, some peculiar aspects have to be discussed.

Conventional diathermy for hemostasis results in closure of vessels, reducing the blood supply of the wound margins. Furthermore, adjacent skin and subcutaneous tissue are also coagulated and may become necrotic. Theoretically, the compression of blood vessels by subcutaneous water edema might overcome this problem. But, even with the waterjet technique, there is an occlusion of the blood supply to the wound edges for the duration of the procedure. Nevertheless, at the end of the operation, with removal of retractors and clips, blood supply to the wound edges remains, because no coagulation was performed. The question whether this indeed results in superior wound healing with less wound edge necrosis and infection must be the focus of future studies.

The accurate separation of dura or dural substitute and skin flap in cranioplasties after previous decompressive craniectomies is very important, because opening of the intradural space, with a subsequent potential risk...
of injury to neural structures and CSF fistula should be avoided. The technique we present offers the possibility of separating skin from dura mater with high accuracy and reliability while safely preserving the dura. The number of patients in our study was relatively small. Also, the interface between the skin and dura varied greatly from patient to patient. Although these differences are not that significant in pediatric patients, the waterjet separation technique might very well cause a dural tear or even longitudinal cutting in fragile, thin dural specimens. This potential risk should be addressed in future studies.

Finally, the application of several liters of separation fluid to an open wound, with subsequent spilling of the fluid all over the surgical field needs further investigation. In the intracranial application, there has been no sign of an increased infection rate with this technique, based on the results of > 200 procedures. However, such a high volume of separation fluid has not been applied in any of these procedures. Especially for small children, an application medium warmed to normal body temperature should be used, which will minimize surgery-related body temperature decrease. Thus, particular attention must be paid to the potential infection rate and further potential risk of this technique in future waterjet cranioplasties.

In all, the waterjet dissection technique could offer distinct advantages in pediatric cranioplasty, with superior scar and dura preparation and wound dissection. The possibility of gentle and safe dura separation could extend the scope of surgical indications for waterjet dissection in neurosurgery. With respect to pediatric neurosurgery, safe sinus separation in craniotomy or craniectomy procedures, like suture resection in craniostenosis, could present further potential indications.

Conclusions

Waterjet dissection in pediatric cranioplasty is a new and safe operative technique for gentle preparation of large skull defects while preserving the dura or dural repair patches. The newly observed hemostasis effect of the waterjet reduces surgery-related blood loss.

Disclosure

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References

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