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ORIGINAL ARTICLE

Efficacy and safety of durotomy after decompressive hemicraniectomy in traumatic brain injury

R. B. Moringlane[1,2] **· N. Keric**[1,2] **· F. B. Freimann**[1] **· D. Mielke**[1] **· R. Burger**[1] **· D. Duncker**[1,3] **· V. Rohde**[1] **· K. L. V. Eckardstein**[1]

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Abstract Decompressive hemicraniectomy (DH) plus duroplasty was demonstrated to be effective for treating critically elevated intracranial pressure (ICP). In order to shorten operation time and to avoid the use of autologous or heterologous material, durotomy has been introduced as an alternative to duroplasty. Only limited data is available on the effect of DH and durotomy on the increased ICP in traumatic brain injury (TBI). Therefore, we collected consecutive intraoperative ICP readings during the different steps of DH and durotomy in TBI patients. Eighteen patients with TBI and uncontrollable ICP increase (measured by either an intraparenchymal or an intraventricular ICP probe) underwent DH and durotomy. ICP readings as well as mean arterial blood pressure (MAP) and arterial PCO_2 were obtained during defined stages of the operation. Surgical complications of the durotomy itself and of cranioplasty after 3 months were recorded. The outcome was assessed prior to cranioplasty using the Glasgow Outcome Scale (GOS). ICP dropped significantly during surgery from a mean of 41 (± 16.2) mmHg at the beginning to a mean of 11.8 (± 7.5) mmHg at the end ($p \leq 0.001$). A first significant ICP-decrease to a mean of 18 (± 10.8) mmHg ($p \leq 0.001$) was detected after removal of the bone flap, and a second significant ICP-decrease to a mean of 10.6 (± 5.3) mmHg ($p < 0.001$) during durotomy. The mean operation time was 115.3 min (± 49.6). Five patients (28%) died; seven patients (39%) had a good outcome (GOS 5). There were no relevant complications associated to durotomy. Durotomy after DH is a safe and straightforward procedure, which significantly lowers critically increased ICP in patients with TBI. Although no graft is used, dural preparation for cranioplasty at 3 months is easily possible.

Keywords Brain injury · Durotomy · Hemicraniectomy

Introduction

Decompressive hemicraniectomy (DH) is widely used to lower critically increased intracranial pressure (ICP) after ischemic stroke, subarachnoid hemorrhage, and traumatic brain injury (TBI) [5, 6, 13, 17–19, 28]. DH has also been performed in the treatment of intracerebral hemorrhage and traumatic subdural hematoma [14, 22, 25, 28, 29]. To achieve and maintain an optimal ICP-decrease, circular, cruciate, or stellate dura opening followed by duroplasty using a hetero- or autologous dura substitute is advocated after removal of the bone flap [7].

In 2008, the technique of simple dural incisions ("durotomy") after DH for malignant cerebral infarction, subarachnoid hemorrhage and intracerebral hemorrhage have been introduced by Schneck and Origitano and by us [4, 26]. Shorter operation time and avoidance of dura substitutes (possibly linked to a lower infection rate) had been considered as potential benefits if compared with duroplasty. This technique was established as standard operating procedure in our institution for all DHs since 2005. The clinical results suggested an adequate ICP-reduction, but the exact effect of durotomy on the elevated ICP never had been examined in a structured way. Furthermore, only limited

R. B. Moringlane, N. Keric, V. Rohde and K. L. V. Eckardstein contributed equally to this work.

✉ R. B. Moringlane
Rene.moringlane@unimedizin-mainz.de

1 Department of Neurosurgery, University Medicine Göttingen, Georg-August University, Göttingen, Germany

2 Department of Neurosurgery, University Medical Centre, Johannes Gutenberg-University, 55131 Mainz, Germany

3 Department of Cardiology and Angiology, Hannover Medical School, Hannover, Germany

data on DH and durotomy in malignant brain edema after TBI is available.

Here, we aimed to assess the effect of durotomy on ICP values and its surgical safety by retrospectively analyzing prospectively collected data of consecutive subacute TBI cases necessitating DH after failure of medical management to control elevated ICP.

Materials and methods

Patient sample and study design

The medical records of TBI patients admitted to our institution from June 2008–June 2012 who were primarily equipped with intraparenchymal or intraventricular ICP probe for monitoring reasons and underwent a DH in the further course were retrospectively reviewed. ICP values continuously >25 mmHg resistant to maximum conservative treatment lead to the indication for DH.

Demographic, clinical, and diagnostic data such as gender, age, patient history, computed tomography (CT) findings, intraoperative measures, complication rate, and clinical outcome prior to cranioplasty (assessed by Glasgow Outcome Scale [GOS]) were collected. Intra-operative ICP values were documented at predefined stages as follows: (1) before skin incision, (2) after each of the first four burr holes, (3) after removal of the bone flap, (4) after each of the five dural incisions, (5) after skin closure, and (6) after removal of the Mayfield clamp. Mean arterial blood pressure (MAP) and the arterial PCO_2 were assessed before skin incision, after bone flap removal, and at the end of the procedure.

All patients obtained a postoperative CT scan 4 h after skin closure. These images were analyzed in consideration to the extent of DH, complications, and possible durotomy effects like brain herniation.

Surgical technique

The side for DH was chosen regarding the main pathology, while bilateral similar injury leads to DH of the contralateral side of the ICP probe. A large skin incision was performed in a reverse question mark shape. A combined skin-muscle flap was prepared. Up to seven burr holes followed by a craniectomy aiming an antero-posterior diameter of approximately 15 cm were performed to achieve a sufficient decompression. Durotomy was carried out with four to five separate dural incisions of 8 to 10 cm length, beginning from the parasagittal region directing to the temporal lobe (Fig. 1). Subgaleal drainage was placed for 24 h.

The survivors obtained autologous bone flap cranioplasty 3 months after DH. The skin was re-opened and again a skin-muscle flap was dissected from the neo-dura. No special technique was necessary for dissecting the neo-dura from the skin-muscle flap. The muscle was then prepared separately and after re-implantation of the autologous bone flap with screws and mini plates fixed on the bone flap.

Statistical analysis

ICP values were analyzed using a linear model adjusted by heterogeneous autoregressive covariance structure and robust standard errors in order to avoid the influence of missing values. Further a *t* test for parametric variables was performed to explore a statistical significance between the ICP values at different predefined surgical steps. The significance level was set $\alpha < 0.05$. All other data are (expressed in mean ± SD (standard deviation)) presented for descriptive reasons and were regarded as explorative.

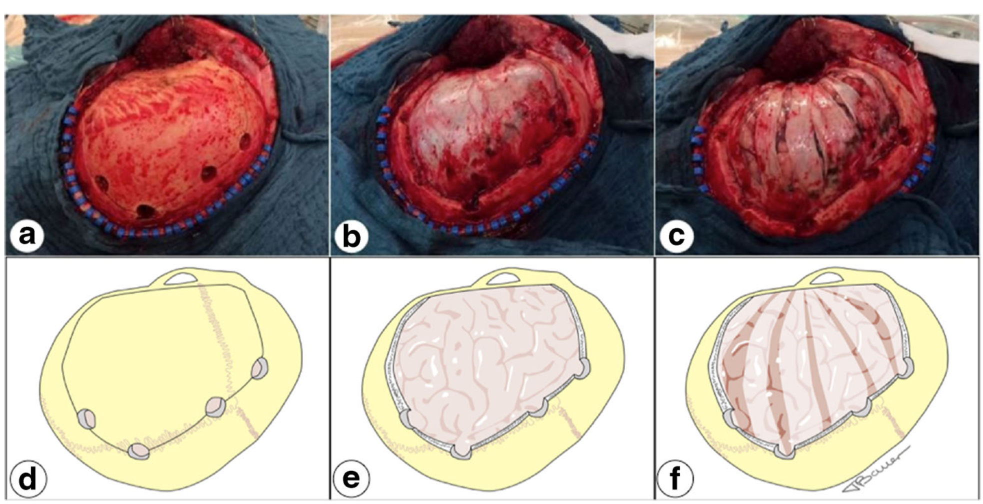

Fig. 1 Intraoperative and schematic images of decompressive hemicraniectomy and durotomy. **a**, **d** Exposed hemicranium and burr holes. **b**, **e** Removal of the bone flap, dura still intact. **c**, **f** After durotomy

Results

Patients

Eighteen patients with a mean age of 37.4 (± 15.5) years were included in this series (14 male, 4 female). Main reasons for TBI were motor vehicle accident (10 patients, 55.5%) and fall from height (7 patients, 39%). In one patient, the reason remained unclear.

Intraoperative measures—ICP, MAP, and pCO_2

Mean ICP values prior to skin incision were 41 (± 16.2) mmHg. No relevant change was observed until the fourth burr hole, while afterwards, a moderate but not significant ICP-decrease (mean 33 ± 15.7 mmHg) could be recorded. The first statistically significant ICP-reduction was noted after bone flap removal—the ICP dropped to a mean of 18 mmHg ($p < 0.001$). (± 10.9). Durotomy leads to a further significant ICP-reduction (mean 10.6 mmHg (± 5.3); $p < 0.001$). ICP-decrease was observed after each dural incision, whereas only the second incision leads to a significant change (Fig. 2). In nine patients, ICP values were recorded continuously in the next 7 days after DH; they showed a mean of 9 (±9.1) mmHg 24 h postoperatively and a slight increase till a mean of 16 (± 6) after 7 days (Fig. 3).

Mean MAP at the time of skin incision was 84.3 mmHg (± 3.8); these values showed no relevant change during the operation. Mean arterial pCO_2 at the time of skin incision was 35.3 mmHg (±6.2), 32.1 mmHg (± 4.7) at bone flap removal, and 33.1 mmHg (± 5.9) at skin closure. Three patients suffered additionally from severe pulmonary injury and showed high pre-operative arterial pCO_2 values (41, 42, and 44 mmHg), which did not improve markedly during surgery. The mean preoperative arterial pCO_2 value of the other 15 patients was 31.4 (± 2.2) mmHg.

Mean operation time of all patients was 115.3 min (± 49.6). Four of the 18 patients had very long operation times. A detailed analysis revealed that one patient had to be immediately re-operated after skin suture due to a massive subgaleal hematoma (operation time 225 min). In one patient, the superior sagittal sinus was injured during craniectomy, and bleeding from a Paccioni granulation leads to a longer operation time (180 min), and in two patients, coagulopathy leads to a very difficult hemostasis (operation time 180 and 160 min). The other 14 patients had a mean operation time of 87.7 min (± 23.7).

Outcome measures

The follow-up period was 3 months. Within this period, three patients required revision surgery due to wound healing problem, epidural empyema, and epidural/subgaleal hematoma ($n = 1$ each). Further neurosurgical operations were necessary due to posthemorrhagic hydrocephalus ($n = 3$), contralateral intracerebral hemorrhage ($n = 1$), contralateral subdural hematoma ($n = 2$), and hygroma ($n = 1$). Despite unilateral DH and intensive conservative treatment, one patient required a contralateral DH to lower uncontrollable ICP values.

The mean bone flap diameter was 14.8 cm (± 1.6 cm). No brain tissue herniation through dural incisions was observed in the post-operative CT scans (Fig. 4).

Five patients (28%) died during hospital stay despite best surgical and medical treatment. Thirteen patients (72%) were seen 3 months after DH and underwent autologous bone flap cranioplasty.

Mean operation time for cranioplasty was 130 min (± 13.2). No special dissection technique has to be applied after initial durotomy. In two cases, small dural tears occurred.

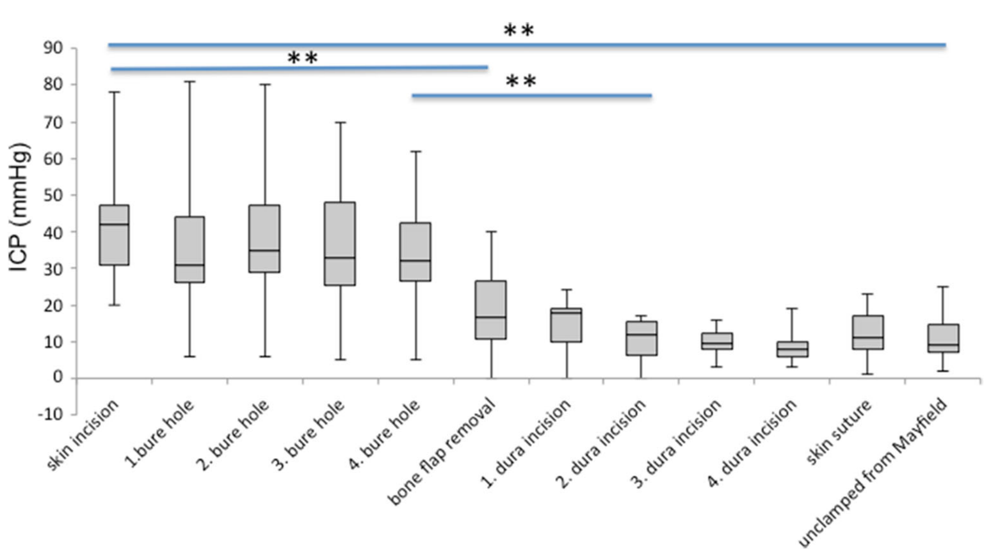

Fig. 2 ICP values at the different surgical steps. *Boxes* show the median ICP values and the p25 to p75 range. Whiskers showing the minimum and maximum ICP values. *Two stars* indicate significance $p < 0.001$

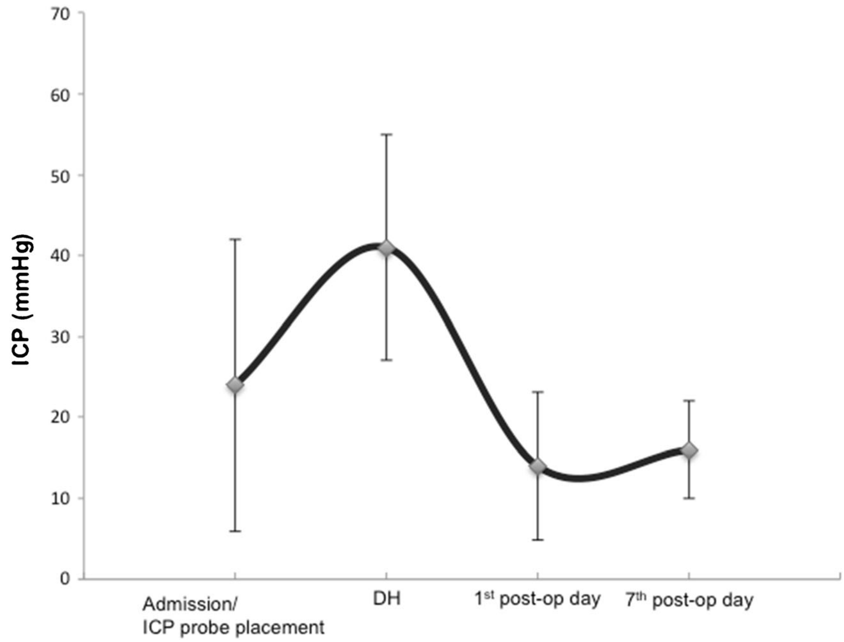

Fig. 3 Course of ICP during the first 7 days (9 of 18 patients). *1* After admission and ICP probe placement, *2* Before DH, *3* 24 h after DH, and *4* 7 days after DH

A routine postoperative CT scan showed no brain injury. In the further course an aseptic and a septic bone necrosis was observed.

The GOS-assessed 3 months after DH revealed that four patients remained in a vegetative state (GOS 2), two patients (11%) were severely disabled (GOS 3), and seven patients (39%) showed a good recovery (GOS 5).

Discussion

Decompressive hemicraniectomy (DH) is a therapeutic option for treatment of critically elevated ICP of different etiologies, including TBI [10, 23]. No generally accepted guidelines exist, when DH in TBI with malignant brain edema should be performed [8, 20, 21, 27]. Patients with ICP values exceeding

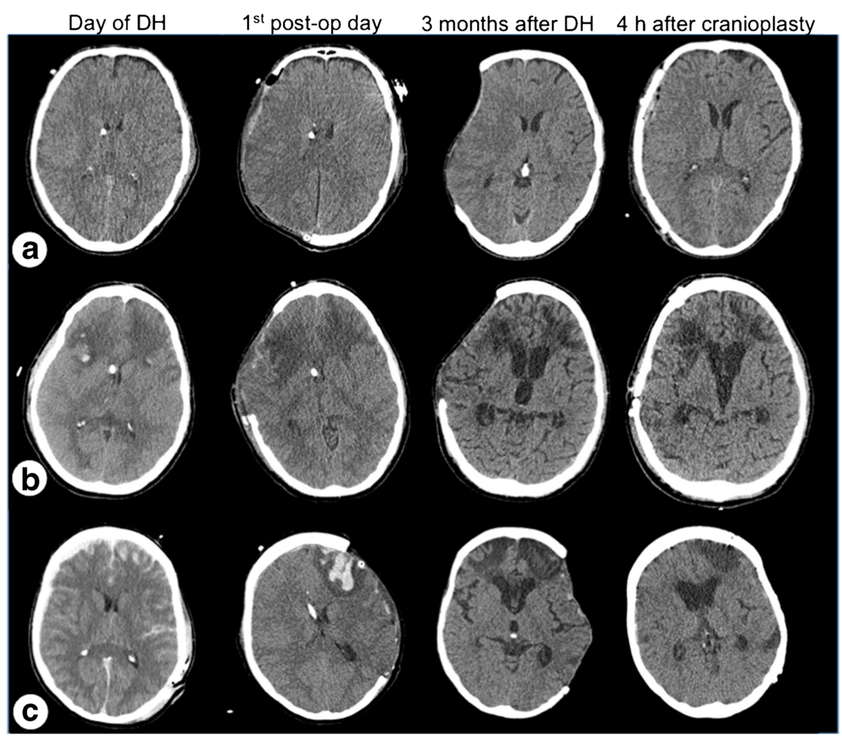

Fig. 4 CT images of three patients (**a**, **b**, **c**) at four different time points. *1* Before DH, *2* After DH, *3* 3 months after DH and prior to cranioplasty, and *4* After cranioplasty

constantly 20–25 mmHg despite adequate conservative treatment are considered to be good candidates for surgery, especially if they are of younger age [6]. Once the decision to perform DH is made, the question of the best surgical technique arises. A duroplasty is widely used after removal of the bone flap and circular, cruciate, or stellate opening of the dura in order to enlarge the intradural space [7, 16, 24, 30]. The major limitation of duroplasty is the additional operative time in a critically ill patient, who best benefits from the controlled situation and monitoring of the intensive care unit [16]. Another minor drawback is the frequent need for heterologous material. Durotomy was introduced as a simple technique to overcome these particular limitations and applied in malignant cerebral infarction and brain edema after subarachnoid and intracerebral hemorrhage [4, 26]. Dedicated studies on DH and durotomy in the treatment of malignant brain edema after TBI do not exist to our knowledge. Furthermore, the influence of the different surgical steps of DH and durotomy on the increased ICP never had been investigated in a structured way.

Effect on ICP

Our data demonstrate a significant ICP-decrease to normal values after DH and durotomy in TBI patients. It is striking that removal of the bone flap already lowers the ICP to a mean of 18 mmHg. However, physiological ICP values could only be achieved by dural incisions. As no comparable data were available in cases of duroplasty, it remains unclear whether one of the both procedures is superior in achieving ICP-reduction. However, as durotomy reached normal ICP values, a possible further effect of duroplasty on ICP-reduction seems negligible. The mean arterial pCO_2 values assessed at the beginning of surgery (35.3 ± 6.2 mmHg) minimally decreased during the operation (33.1 ± 5.9 mmHg). Except of three patients, who suffered from severe pulmonary injury resulting in high initial arterial pCO_2, all patients underwent hyperventilation with low arterial pCO_2 values. These values did not notably change during surgery, so that ICP-decrease cannot be attributed substantially to additional hyperventilation.

Duration of surgery

The mean operation time of 115.3 min (± 49.6) appears long. However, it has to be mentioned that the range was wide with 45 to 225 min. Moreover, four cases necessitated longer operation times due to large subgaleal hematoma after skin closure and immediate re-operation, injury of the superior sagittal sinus, and bleeding from Paccioni granulations and two cases of anticoagulation with platelet-aggregation-inhibitors, making hemostasis more difficult. Güresir et al. described a rapid closure technique after DH. They opened the dura in a stellate fashion and covered it by hemostyptic material. In their series of 341 DH's, they reported a mean operation time of 69 ± 20 min. They compared their data with cases of DH followed by duroplasty reported by Horaczek et al. Their mean operation times were significantly lower (69 ± 20 versus. 122.8 ± 43.4 min, $p < 0.0001$) [12, 16]. Rare data concerning duration of DH and duroplasty are available in the literature. As most published data report of duroplasty, comparison with our data is not possible. However, in their analysis of a dural substitute as onlay compared to watertight duroplasty after DH, Horaczek et al. found a significant lower operation time in the onlay group. (96.2 ± 32.1 versus 122.8 ± 43.4) [16].

The surgical time for cranioplasty of our series is in range with reports of the literature, while Güresir et al. reported of 107 ± 33 min [12]. In the comparison of a dural substitute as an onlay and watertight duroplasty the mean operation time in the onlay group was 112 ± 49.1 versus 139.3 ± 56.8 min [16]. Neurosurgical residents mainly performed all cranioplasty procedures with assistance of a consultant neurosurgeon. The surgical experience can also be an influencing factor on the operation time.

Outcome

Performing DH and durotomy, we obtained a favorable outcome (GOS 4 and 5) in 38.8% of the patients; the mortality rate was 28%. These clinical results are well comparable with the published results of DH and duroplasty in TBI. In a study of 40 patients, a good recovery (GOS 4 and 5) was found in 25%, while the mortality rate was 42.5% [2]. Gouello et al. reported in their study of 60 patients a favorable outcome in 23%; the mortality rate was 17% [11]. Aarabi et al. reported a good outcome in 51.3% and a mortality rate of 28% [1]. In these clinical series, acute DH and delayed DH were performed, while our series includes only patients, who obtained delayed DH when ICP became refractory to medical treatment. This fact makes a comparison with outcome data from the literature mentioned above difficult. Nevertheless, our outcome data suggest that the volume gain for the brain after DH and durotomy is sufficient and effective for subacute TBI patients.

Complications

Three complications directly related to surgery occurred. There were one wound infection, one subdural empyema, and one subgaleal hematoma. The infection rate of 11% is in line with the published literature on DH and duroplasty. Not the way of dura opening, but presumably the large operative field which is needed for bone removal, plus impaired microcirculation caused by the administration of high catecholamine dosages for maintenance of a cerebral perfusion pressure are more likely the main factors for disturbed wound healing and infection. Shorter surgery and avoidance of alloplastic material in DH and durotomy theoretically should have a positive effect on the infection rate; however, the patient population clearly was far too small to detect this effect.

In contrast to duroplasty, the dura after durotomy stays open. Nonetheless, we did not observe a single case of CSF fistula but one case of subdural hygroma (5.5%). The swollen brain might expand and block the dural slots avoiding CSF leakage into the epidural space resulting in a fistula. Postoperative CT scans, which were routinely performed 4 h after surgery, and if necessary for therapeutic decision-making, ruled out no brain herniation. In contrast, brain herniation had been observed in up to 25.6 to 36% of the patients undergoing duroplasty, which could have the consequence of kinking of cortical brain draining veins at the dural edge, thereby further enhancing brain swelling and contributing to poor outcome [15, 32].

Not related to DH and durotomy, but presumably to the warranted decompressive effect of surgery in combination with the ongoing dynamics of a severe TBI, contralateral intraparenchymal (n = 1) and remote subdural hematoma (n = 2) occurred and necessitated neurosurgical treatment. There were three cases of posttraumatic hydrocephalus (17%), which are not attributable to the surgical therapy and operative technique but are the sequelae of altered CSF circulation after TBI. The rate of posttraumatic hydrocephalus is in line with the percentages given in the literature [15]. The incidence of subdural hygroma (5.5%) is low in comparison to other series. Yang et al. in their series of 108 TBI patients undergoing DH and duroplasty observed subdural effusions in 21.3% [32], and Honeybul et al. in their series of 78 TBI patients undergoing DH plus duroplasty in 49.4% [15]. According to the literature, another frequent complication after DH and duroplasty are postoperative seizures, which are seen in up to 22% [15]. In our series no seizures occurred during the follow-up period. It remained unclear why the rate of subdural hygroma and seizures are substantially lower in the present series of DH and durotomy compared to DH and duroplasty.

Cranioplasty

Re-implantation of the autologous bone flap was carried out successfully in 13 patients 3 months after DH. One might assume that the absence of a layer between the brain surface and the skin flap after durotomy might render tissue preparation for bone flap re-implantation more difficult with a higher risk of CSF flow. However, we did not encounter the problem of a lacking cleavage plane between skin flap and CSF space and of CSF fistula. As complication after cranioplasty, we observed one case of aseptic and septic bone necrosis each. This complication rate of 11% is low if compared with the literature. Aseptic necrosis of the bone flap is the most frequent complication of cranioplasty and occurs in up to 22.8% [3, 9, 31].

Limitation of the study

The best way to show the non-inferiority of DH and durotomy in comparison to DH and duroplasty would have been a prospective randomized trial. After the present study which documented immediate ICP normalization after durotomy, low rate of surgery-associated complications and outcomes which are as good as those of DH and duroplasty, it is very unlikely, that a prospective trial, which is adequately powered, will be initiated in the future. Another, but inferior option would have been a comparison of the prospectively collected durotomy data with retrospective data of DH and duroplasty from the same institution. However, beginning in 2005, after having changed to the current institution, the senior author (VR) developed standard operative procedures for the conservative management of TBI patients, defined the criteria for DH, and introduced the technique of durotomy, not allowing a scientifically meaningful comparison with institutional data before 2005. Therefore, a prospective data collection with a special, so far not well-investigated focus on the effect of distinct surgical steps on ICP was considered to be the best study design. One might criticize the limited number of patients. According to the institutional protocol, DH and durotomy was only performed in persistent ICP >25 mmHg despite CSF drainage and use of barbiturates and after exclusion of a space-occupying hematoma, and was never part of initial surgery for hematoma removal, which might explain the low patient number. Furthermore, a major focus of the study was the measurement of the ICP at the different surgical steps of DH and durotomy. As rapid normalization to normal ICP values has been consistently shown, we do not believe that a higher patient number would have let to divergent results.

Conclusion

We conclude that durotomy after DH is a fast and safe procedure, which rapidly achieves a significant decrease of critically elevated ICP values following TBI. The rates of favorable outcome and mortality are as good as or even better than those reported for DH and duroplasty, which might indicate that the volume gain for the brain is comparable with that of duroplasty while avoiding the risk of prognostically poor brain herniation at the duroplasty edges. It is not accompanied with higher complication rates. Durotomy should be considered as an alternative to duroplasty when performing DH.

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Compliance with ethical standards

Authors' statement No funding has been received for this study.

This study is a retrospective analysis of a consecutive case collection; the operative technique represents a standard procedure in the neurosurgical department of the University of Göttingen. According to the laws of the local ethical review board, for this kind of study, no specific approval is necessary.

As described in (C), the presented operating procedure is a local standard. Apart from the informed consent for the surgical procedure from patient or relatives, no further informed consent was obtained.

Conflict of interest The authors declare that they have no conflict of interest.

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