# Reduction in wound healing complications and infection rate by lumbar CSF drainage after decompressive hemicraniectomy

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**OBJECTIVE** Wound healing disorders and surgical site infections are the most frequently encountered complications after decompressive hemicraniectomy (DHC). Subgaleal CSF accumulation causes additional tension of the scalp flap and increases the risk of wound dehiscence, CSF fistula, and infection. Lumbar CSF drainage might relieve subgaleal CSF accumulation and is often used when a CSF fistula through the surgical wound appears. The aim of this study was to investigate if early prophylactic lumbar drainage might reduce the rate of postoperative wound revisions and infections after DHC.

**METHODS** The authors retrospectively analyzed 104 consecutive patients who underwent DHC from January 2019 to May 2021. Before January 2020, patients did not receive lumbar drainage, whereas after January 2020, patients received lumbar drainage within 3 days after DHC for a median total of 4 (IQR 2–5) days if the first postoperative CT scan confirmed open basal cisterns. The primary endpoint was the rate of severe wound healing complications requiring surgical revision. Secondary endpoints were the rate of subgaleal CSF accumulations and hygromas as well as the rate of purulent wound infections and subdural empyema.

**RESULTS** A total of 31 patients died during the acute phase; 34 patients with and 39 patients without lumbar drainage were included for the analysis of endpoints. The predominant underlying pathology was malignant hemispheric stroke (58.8% vs 66.7%) followed by traumatic brain injury (20.6% vs 23.1%). The rate of surgical wound revisions was significantly lower in the lumbar drainage group (5 [14.7%] vs 14 [35.9%], p = 0.04). A stepwise linear regression analysis was used to identify potential covariates associated with wound healing disorder and reduced them to lumbar drainage and BMI. One patient was subject to paradoxical herniation. However, the patient's symptoms rapidly resolved after lumbar drainage was discontinued, and he survived with only moderate deficits related to the primary disease. There was no significant difference in the rate of radiological herniation signs. The median lengths of stay in the ICU were similar, with 12 (IQR 9–23) days in the drainage group compared with 13 (IQR 11–23) days in the control group (p = 0.21).

**CONCLUSIONS** In patients after DHC and open basal cisterns on postoperative CT, lumbar drainage appears to be safe and reduces the rate of surgical wound revisions and intracranial infection after DHC while the risk for provoking paradoxical herniation is low early after surgery.

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**KEYWORDS** lumbar drainage; wound healing; decompressive hemicraniectomy; malignant hemispheric stroke; traumatic brain injury; infection; paradoxical herniation; surgical technique; vascular disorders

Decompressive hemicraniectomy (DHC) is a lifesaving procedure in patients with refractory increased intracranial pressure (ICP), allowing for brain swelling and increased cerebral perfusion. Several studies have demonstrated the efficiency of the procedure in reducing a patient's mortality in cases of malignant hemispheric stroke (MHS), intracerebral hemorrhage (ICH), or severe traumatic brain injury (TBI).[1–5] However, DHC is

**ABBREVIATIONS** DHC = decompressive hemicraniectomy; EVD = external ventricular drain; ICH = intracerebral hemorrhage; ICP = intracranial pressure; MHS = malignant hemispheric stroke; mRS = modified Rankin Scale; TBI = traumatic brain injury.

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an invasive procedure that exposes patients to significant risks, with rates of up to 74% for numerous DHC-associated complications that might prolong the clinical course and further compromise the already poor prognosis.[6–9]

In the early postoperative period, the most frequently encountered complications are wound healing disorders and surgical site infections.[6,7] In the literature, the rate of wound complications varies between 3% and 40%.[10] The main reason for the higher rate of wound healing complications compared with standard craniotomy for most neurosurgical procedures is the large incision and skin bone flap as well as the need for an extended decompression with exposure of the temporal base. This increases the risk of injuring the superficial temporal artery, which reduces scalp flap perfusion and predisposes the wound to ischemia and healing disorders.[8] Furthermore, the often-exercised rapid closure technique leaves the dura placed loosely over the exposed brain and a watertight closure is rarely achieved, even with duroplasty.[11,12] Subsequent CSF leakage has been described in up to 6.7% of TBIs and 8.8% of stroke cases.[7] However, the high rate of wound healing complications after DHC is mainly associated with subgaleal fluid accumulation on the ipsilateral side of the craniectomy, often a mixture of postoperative hematoma and CSF. Extra-axial CSF collection is a well-known complication after DHC and usually occurs within the 1st postoperative week in up to 27%–57% of patients.[6,13,14] Despite its generally benign course, persistent subcutaneous CSF accumulation can cause a tense and bulged skin flap and might increase the risk of wound dehiscence, CSF leakage, and surgical site infection. Thus, the aim of this study was to test the hypothesis that early lumbar CSF drainage after DHC might decrease postoperative subgaleal CSF accumulation and thereby reduce the high rate of severe wound healing complications and infections. We also focused on demonstrating that early lumbar CSF drainage within the 1st postoperative week is safe, and we assessed drainage-associated complications and signs for herniation.

# Methods

## Study Design and Patient Population

This retrospective cohort study was approved by the ethics committee of the Charité—Universitätsmedizin Berlin and was performed in compliance with Health Insurance Portability and Accountability Act regulations. Patient consent was not required because of the retrospective nature of the study. Data acquisition and presentation were done according to the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) guidelines for reporting observational studies.[15]

We identified all subsequent patients who underwent DHC for an MHS, severe TBI, or ICH at the Department of Neurosurgery at Charité University Hospital Berlin between January 2019 and May 2021. Demographic, clinical, and radiographic patient data were retrospectively extracted from clinical records and documentation and included patient-specific risk factors for wound healing disorders (BMI, diabetes mellitus types 1 and 2, smoking, hypertension, chronic kidney disease, coronary or peripheral artery disease, and previous stroke).

## Surgical Procedure and Neurointensive Care

DHC was performed as previously described.[12,16,17] According to our institutional guidelines, every patient received a single shot of 2 g of cefazolin intravenously and a bodyweight-adapted dose of 50 mg/kg of mannitol 30 minutes before skin incision. In patients with a known allergy to cefazolin, 600–900 mg of intravenous clindamycin was administered instead. Hemicraniectomy was performed with a diameter of at least 11 × 15 cm of bony decompression. After durotomy, the dura was replaced loosely over the exposed brain. In each patient, a parenchymal probe for ICP monitoring was placed during the surgery along with a subgaleal Robinson drain. All patients were referred to the neurointensive care unit following DHC and were treated according to the guidelines of the German Society of Neurosurgery. In the first 24 hours after surgery, systolic blood pressure < 140 mm Hg, mean cerebral perfusion pressure > 65 mm Hg, normothermia < 37.5°C, and normoglycemia were maintained. Routine postoperative CT was performed within 24 hours after surgery to rule out procedure-related complications and to evaluate the basal cisterns. The Robinson drain was removed within the first 24–36 hours after surgery in all groups. In the lumbar drainage group, patients received a lumbar drainage with continuous CFS drainage of 5 ml/hr started within the first 3 days after DHC. ICP was recorded continuously via an intraparenchymal probe and via the CSF drainage with the pressure transducer of the lumbar drain leveled at the external acoustic meatus (Fig. 1). Controlled CSF drainage was done only if the difference between the ICP recorded with the intraparenchymal probe and the pressure recorded with the lumbar drain was less than 5 mm Hg and only after the postoperative CT scan confirmed open or compressed but no absent basal cisterns. Critical ICP > 20 mm Hg was treated according to national and international guidelines with CSF drainage either through an external ventricular drain (EVD) or lumbar drain, osmotic therapy, and deep sedation. Complications at the surgical site with the need of surgical revision were defined as severe wound healing events.

## CT Scan Analysis

CT scans were analyzed by two neurosurgeons unaware of the drainage group. Definitions of determined parameters according to Münch et al. are shown in Fig. 2.[18] We analyzed radiological features on CT scans during the lumbar CSF drainage period within the 1st postoperative week and all CT scans within 21 days after DHC, including the occurrence and thickness of hygroma and subgaleal CSF accumulations; signs of subfalcine, transtentorial, and tonsillar herniation; and the status of the ventricles and basal cisterns according to whether they were well defined and visible, compressed, or absent. We aimed to distinguish between subgaleal CSF accumulations and subdural hygromas based on a definable dural layer on the postoperative CT scan.

## Statistical Analysis

Data were analyzed using the Mann-Whitney U-test and Pearson's chi-square test. Two-sided p values < 0.05

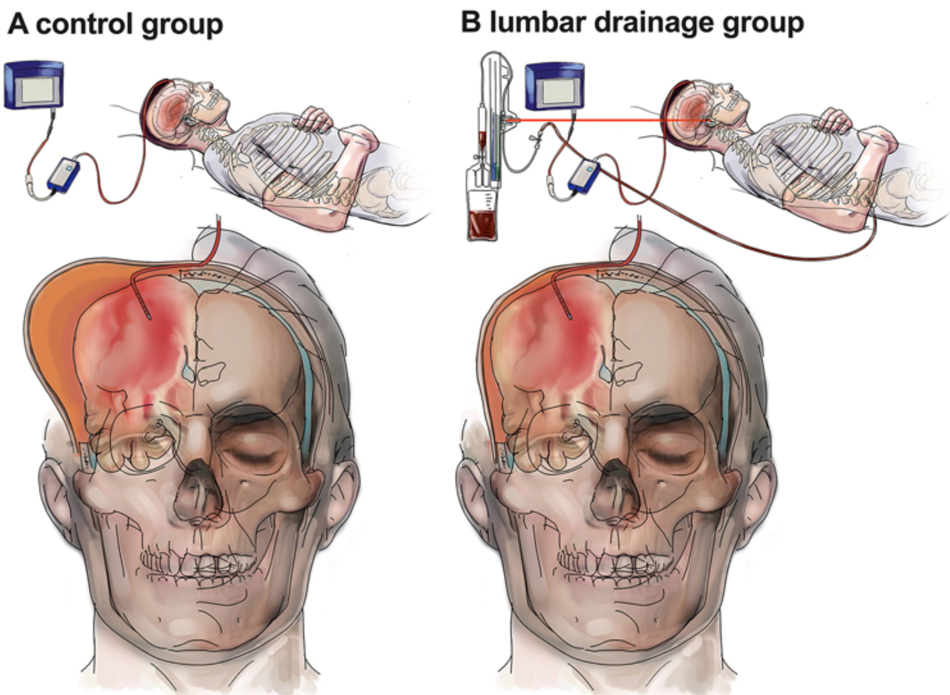


**FIG. 1.** Study design **A:** Control group without lumbar CSF drainage and increased subgaleal CSF accumulation causing additional tension to the wound. **B:** Combined ICP monitoring and lumbar CSF drainage with reduced subgaleal CSF accumulation and relaxed wound conditions. The pressure transducer of the lumbar drain is leveled at the external acoustic meatus. CSF is only drained if the difference between the ICP and the pressure measured with the lumbar drainage is less than 5 mm Hg. © Lucius Samo Fekonja, published with permission. Figure is available in color online only.

were used to indicate statistical significance. A forward stepwise linear regression model was used to identify possible predictors of wound healing complications requiring surgical revision as the outcome variable out of the following candidate variables: age, sex, diabetes mellitus, smoking, coronary or peripheral artery disease, previous stroke, hypertension, chronic kidney disease, radiological occurrence of hygroma and subgaleal CSF accumulation, BMI, duration of the surgery, and use of a lumbar CSF drain. At each step, the program's default selection criteria for independent variables were $p < 0.05$ to enter and $p > 0.10$ to remove. Multicollinearity was tested using the Pearson correlation coefficient. An absolute correlation coefficient of > 0.7 among two or more predictors was chosen to indicate the presence of multicollinearity. For all analyses, IBM SPSS (version 27, IBM Corp.) and Prism 9 (version 9.2.0, GraphPad Software) were used. There were no missing data for the analyzed variables.

## Results

### Patient Cohort

At our institution, 104 patients underwent a DHC between January 2019 and May 2021. Thirty-one patients died during the acute phase of non–drainage-related complications, resulting in an in-hospital mortality of 29.8%. These patients were excluded from the primary analysis of endpoints but remained for safety analysis; thus, 74 patients were included in the endpoint analysis. The CONSORT flow diagram of our study is provided in Fig. 3. The median age of the included patients was 55 (IQR 44–60) years with a male-to-female ratio of 1:1.4. The major underlying pathologies requiring DHC were MHS (63.0%), TBI (21.9%), and ICH (9.6%). Before January 2020, patients did not undergo lumbar drainage, whereas after January 2020,


**FIG. 2.** Parameters shown on a CT scan. d = diameter of craniectomy; p = perpendicular line of largest distance from the diameter to the dural flap.

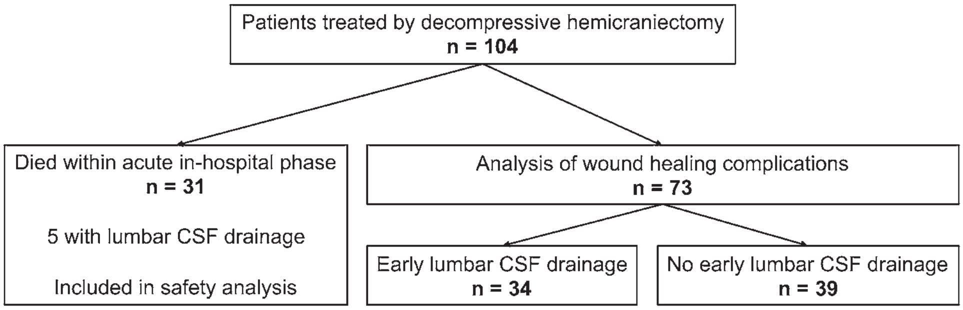


**FIG. 3.** CONSORT flow diagram.

patients underwent lumbar drainage started within 3 days after DHC. Thirty-four patients underwent lumbar drainage within the first 3 days after surgery and were stratified to the lumbar drainage group. In 10 patients, lumbar drainage was performed after the 4th postoperative day as a salvage therapy when wound dehiscence and CSF fistula had already occurred and therefore were allocated to the control group, which comprised 39 patients. In the lumbar drainage group, 30 (88.2%) of the 34 patients had an intraparenchymal ICP probe and 2 patients (5.9%) had an EVD. In the control group, 30 (76.9%) of 39 patients received an intraparenchymal ICP probe and 6 patients (15.4%) had an EVD. Of the 31 patients who died during the acute phase, 5 patients received a lumbar CSF drain and died after withdrawal of care considering the unfavorable neurological prognosis but not due to complications associated with lumbar drainage. Patient-specific risk factors for wound healing disorders did not differ significantly between the two groups except for more previously documented cerebral strokes in the lumbar drainage group. Baseline characteristics are provided in Table 1.

### Lumbar Drainage Management

In the lumbar drainage group, CSF drainage was initiated on day 1 (IQR day 1–2) after DHC, after the first postoperative CT scan showed open (visible or compressed) basal cisterns. CSF drainage was continued for 4 (2–5) days and paused every time the difference between

**TABLE 1. Baseline characteristics and stratification regarding early lumbar drainage**

| | Overall (n = 73) | Control Group (n = 39) | Lumbar Drainage Group (n = 34) | p Value |
|---|---|---|---|---|
| Median age, yrs | 55 (44–60) | 53 (38–60) | 56 (46–59) | 0.56 |
| Female sex | 43 (58.9) | 33 (84.6) | 10 (29.4) | **0.001** |
| Median BMI, kg/m$^2$ | 25.7 (23.1–27.7) | 25.7 (21.5–27.7) | 25.5 (23.7–27.7) | 0.57 |
| DM type 2 | 13 (17.8) | 5 (12.8) | 8 (23.5) | 0.23 |
| Smoking | 12 (16.4) | 5 (12.8) | 7 (20.6) | 0.37 |
| Hypertension | 34 (46.6) | 16 (41.0) | 18 (52.9) | 0.31 |
| CKD | 4 (5.5) | 3 (7.7) | 1 (2.9) | 0.37 |
| CAD/PAD | 11 (15.1) | 5 (12.8) | 6 (17.6) | 0.57 |
| Prior stroke | 6 (8.2) | 0 (0.0) | 6 (17.6) | **0.005** |
| Reason for DHC | | | | 0.51 |
| MHS | 46 (63.0) | 26 (66.7) | 20 (58.8) | |
| TBI | 16 (21.9) | 9 (23.1) | 7 (20.6) | |
| ICH | 7 (9.6) | 2 (5.1) | 5 (14.7) | |
| SAH | 3 (4.1) | 1 (2.6) | 2 (5.9) | |
| Other | 1 (1.4) | 1 (2.6) | 0 (0.0) | |
| DHC | | | | |
| Side of DHC, lt | 39 (53.4) | 24 (61.5) | 15 (44.1) | 0.14 |
| Median max diameter, mm | 158 (151–164) | 159 (151–164) | 158 (150–164) | 0.77 |
| Median bone remnant to temporal base, mm | 5.8 (3.4–9.9) | 5.5 (2.8–8.0) | 6.6 (3.6–11.4) | 0.27 |
| Median duration of op, mins | 113 (94–133) | 108 (93–131) | 116 (99–135) | 0.53 |
| Intraparenchymal ICP monitoring | 60 (82.2) | 30 (76.9) | 30 (88.2) | 0.21 |
| EVD | 8 (11.0) | 6 (15.4) | 2 (5.9) | 0.19 |

CAD = coronary arterial disease; CKD = chronic kidney disease; DM = diabetes mellitus; PAD = peripheral arterial disease; SAH = subarachnoid hemorrhage.
Values represent the number of patients (%) or median (IQR) unless stated otherwise. Boldface type indicates statistical significance.

**TABLE 2. Drainage regimen of lumbar drainage group**

| | Lumbar Drainage (n = 34) |
|---|---|
| Start of drainage, postop day | 1 (1–2) |
| Duration of drainage, days | 4 (2–5) |
| Cumulative amount of drained CSF, ml | 455 (296–659) |

Values represent the median (IQR) unless stated otherwise.

the ICP recorded with the intraparenchymal probe and the lumbar drainage was more than 5 mm Hg. The median cumulative amount of drained CSF was 455 (IQR 296–659) ml (Table 2). The frequency of how often the difference between the ICP and the lumbar pressure measured at the level of the external acoustic meatus exceeded 5 mm Hg could not be assessed retrospectively.

## Surgical Wound Revisions and Outcome

Severe wound healing complications requiring revision surgery occurred in 14 (35.9%) of the 39 patients in the control group and in 5 (14.7%) of the 34 patients in the lumbar drainage group (p = 0.04; Table 3 and Fig. 4A) a median of 17 days after surgery with IQRs of 14–25 and 10–20, respectively. There were fewer purulent wound infections and significantly fewer patients with subdural empyema in the lumbar drainage group (8 vs 0, p = 0.005) (Fig. 4B).

The reduced rate of wound healing complications in the lumbar drainage group was associated with less occurrence of postoperative subgaleal CSF accumulation on the ipsilateral side of the DHC and with a decreased median thickness of the CSF accumulation, with 11 (IQR 8.7–14.0) mm compared with 20.6 (IQR 7.3–24.4) mm in the control group, potentially causing less additional tension to the large skin flap. A forward stepwise linear regression analy-

**TABLE 3. Outcome of patients and stratification regarding lumbar drainage**

| | Overall (n = 73) | Control Group (n = 39) | Lumbar Drainage Group (n = 34) | p Value |
|---|---|---|---|---|
| Primary outcome | | | | |
| SWHE requiring revision op | 19 (26.0) | 14 (35.9) | 5 (14.7) | **0.04** |
| Median postop day of SWHE | 17 (11–24) | 17 (14–25) | 17 (10–20) | 0.64 |
| Secondary outcome | | | | |
| Purulent wound infection | 9 (12.3) | 7 (17.9) | 2 (5.9) | 0.12 |
| Meningitis during hospital stay | 19 (26.0) | 11 (28.2) | 8 (23.5) | 0.65 |
| Subdural empyema | 8 (11.0) | 8 (20.5) | 0 (0.0) | **0.005** |
| Secondary epilepsy | 11 (15.1) | 6 (15.4) | 5 (14.7) | 0.94 |
| Median mRS score at discharge | 5 (5–5) | 5 (5–5) | 5 (5–5) | 0.13 |
| Median ICU length of stay, days | 12 (9–23) | 13 (11–23) | 12 (9–19) | 0.21 |
| CT scan during lumbar drainage period | | | | |
| Median postop day of CT scan | 5 (3–8) | 4 (3–7) | 7 (4–9) | 0.07 |
| Median d/p ratio | 2.9 (2.6–3.3) | 2.9 (2.6–3.5) | 2.9 (2.6–3.2) | 0.34 |
| Hygroma | 27 (37.0) | 12 (30.8) | 15 (44.1) | 0.24 |
| SgCSFA | 10 (13.7) | 6 (15.4) | 4 (11.8) | 0.65 |
| Median thickness, mm | 13.0 (8.1–23.0) | 20.6 (7.3–24.4) | 11 (8.7–14.0) | 0.35 |
| Signs of herniation | | | | 0.55 |
| None | 66 (90.4) | 36 (92.3) | 30 (88.2) | |
| Subfalcine | 6 (8.2) | 3 (7.7) | 3 (8.8) | |
| Transtentorial | 1 (1.4) | 0 (0.0) | 1 (2.9) | |
| Basal cisterns on 1st postop CT | | | | 0.46 |
| Visible | 11 (15.1) | 7 (17.9) | 4 (11.8) | |
| Compressed | 62 (84.9) | 32 (82.1) | 30 (88.2) | |
| Absent | 0 (0.0) | 0 (0.0) | 0 (0.0) | |
| Ventricles | | | | 0.48 |
| Visible | 15 (20.5) | 9 (23.1) | 6 (17.6) | |
| Compressed | 57 (78.1) | 30 (76.9) | 27 (79.4) | |
| Absent | 1 (1.4) | 0 (0.0) | 1 (2.9) | |
| Follow-up scan w/in 21 days post-DHC | | | | |
| Hygroma | 37 (50.7) | 19 (48.7) | 18 (52.9) | 0.72 |
| SgCSFA | 19 (26.0) | 13 (33.3) | 6 (17.6) | 0.13 |

d = diameter of craniectomy; p = perpendicular line of largest distance from the diameter to the dural flap; sgCSFA = subgaleal cerebrospinal fluid accumulation; SWHE = severe wound healing event.

Values represent the number of patients (%) or median (IQR) unless stated otherwise. Boldface type indicates statistical significance.

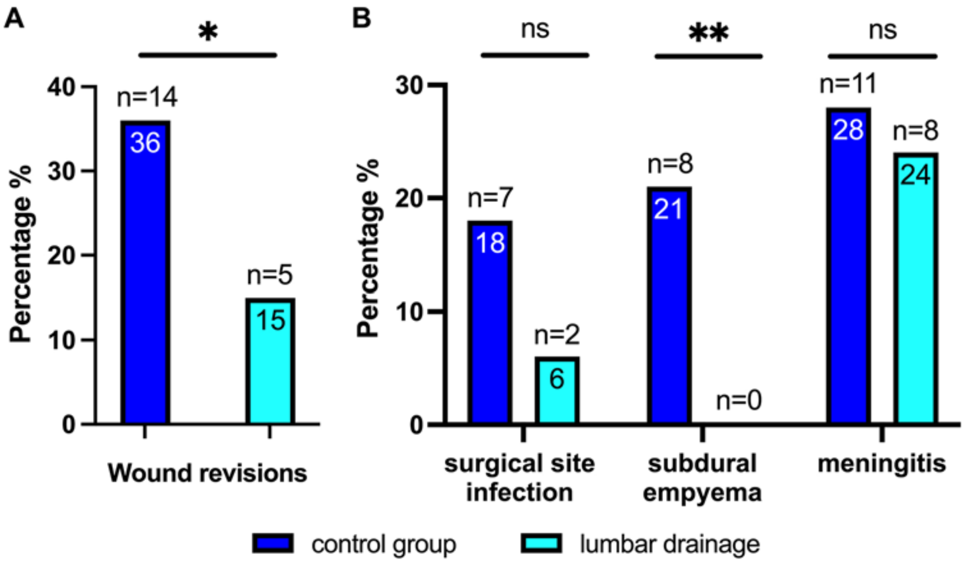


**FIG. 4.** Reduced rate of postoperative wound healing complications and infections in the lumbar drainage group. **A:** Rate of surgical wound revisions for wound healing complications. **B:** Rate of postoperative surgical site and intracranial infections. ns = not significant. *p < 0.05; **p < 0.01. Figure is available in color online only.

sis was used to identify prognostic factors other than lumbar drainage associated with an increased risk for wound healing disorders requiring revision surgery as the outcome variable. The stepwise regression analysis reduced the independent variables to early lumbar drainage (t = –2.31, p = 0.03) and BMI (t = 2.27, p = 0.03) with an adjusted $R^2 = 0.13$, F = 5.13, and p = 0.03 of the model. In the first step, early lumbar drainage was entered in the model with p = 0.04 (F = 5.13, t = –2.12), similar to the result of the chi-square analysis finding a statistically significant group difference in the rate of wound healing disorders requiring surgical revision between the control and the lumbar drainage group with p = 0.04. There were significantly more women in the control group than in the lumbar drainage group (33/39 [85%] vs 10/34 [29%], p = 0.001). However, sex was included in the analysis but was not entered in the model because of missing significance, with p = 0.18 (t = –1.36). There was no relevant multicollinearity among candidate variables using the Pearson correlation coefficients. The highest Pearson correlation coefficient was found among sex and early lumbar drainage with 0.56 and a variance inflation factor of 1.73 for lumbar drainage and 1.71 for sex. Notably, the reduced rate of surgical revisions due to wound healing complications did not seem to decrease the ICU length of stay. There was also no difference regarding functional status and modified Rankin Scale (mRS) score at the time of transfer. Outcome of patients after DHC is provided in Table 3. Overall, 17 (23.3%) of 73 patients developed permanent communicating hydrocephalus with consecutive placement of a ventriculoperitoneal shunt. There was no statistical difference between the lumbar drainage group and the control group (11/34 [32.4%] vs 6/39 [15.4%], p = 0.087).

### Complications

In this study, the rate of bacterial meningitis was similar in both groups, affecting 11 (28.2%) of the 39 patients in the control group and 8 (23.5%) of the 34 patients in the lumbar drainage group and did not seem to be increased due to catheter-associated infections (p = 0.65). There was also no difference in the overall rate or median thickness of postoperative hygroma. However, 2 patients in the lumbar drainage group had to undergo revision surgery with evacuation of progressive hygroma because of increased mass effect with neurological deterioration (Fig. 5). One hygroma developed on the ipsilateral side, and the other developed on the contralateral side and had to be drained through a burr hole. Consecutive CT scans demonstrated well-defined or merely compressed ventricles and basal cisterns in almost all patients, and there was no significant difference in the rate of radiological signs for subfalcine, transtentorial, or tonsillar herniation. In the lumbar drainage group, 1 patient, who was 45 years old and underwent DHC for an MHS, experienced paradoxical transtentorial herniation with neurological deterioration and bilateral dilated pupils on the 6th postoperative day (the 5th day under lumbar drainage). The patient's ICP was normal at this time. The symptoms rapidly resolved after lumbar drainage was discontinued, and the patient was transferred to a neurorehabilitation unit 18 days after DHC. When the patient was readmitted for cranioplasty 4 months after DHC, he presented only with moderate deficits related to the primary disease with an mRS score of 3.

## Discussion

The main finding of our study is that lumbar CSF drainage initiated within the first 3 postoperative days after DHC appears to be safe and decreases the risk of severe wound healing complications requiring revision surgery. Early lumbar drainage was associated with less postoperative subgaleal, extra-axial CSF accumulation in the lumbar drainage group and reduced the rate of purulent wound infections and subdural empyema following wound healing complications and dehiscence. Furthermore, the strict CSF drainage protocol and radiological confirmation of open basal cisterns combined with simultaneous ICP and lumbar pressure monitoring minimized the risk of overdrainage and paradoxical herniation, and radiological CT studies demonstrated no significantly increased signs of subfalcine, transtentorial, or tonsillar herniation under lumbar drainage.

## Wound Healing Disorder

Postoperative subgaleal CSF accumulation is a frequently encountered complication after DHC and occurs in up to 27%–57% of patients.[6,13,14] So far, the impact of subgaleal CSF accumulation on postoperative wound healing disorders has not been investigated.[10] We postulated that the subgaleal CSF accumulation on top of the cerebral edema and brain swelling causes additional tension to the large skin flap and thereby increases the already high risk of wound dehiscence and wound healing complications after DHC. Extra-axial fluid accumulations usually remain asymptomatic and resolve spontaneously within the course of weeks.[9,19,20] It has been suggested that in patients with asymptomatic extra-axial CSF effusion, shunting and early cranioplasty can be avoided because of the self-resolving nature.[21] However, extra-axial fluid accumulations and their complex pathophysiology remain poorly understood.

The main reason for the higher rate of subgaleal CSF accumulation compared with a standard supratentorial craniotomy is supposed to be due to deranged CSF dynamics following the large dural opening and the removal of the large bone flap.[22,23] This might also explain the laterality of almost all postoperative subgaleal CSF accumulations occurring on the ipsilateral side.[14] Another hypothesis proposes that extra-axial fluid accumulation is a manifestation of an external hydrocephalus[24] or that, in the setting of TBI, shear stress generates arachnoid tears in the arachnoid-dura interface layer, allowing CSF effusion into the subdural space.[14,25] The lack of clarity about the pathophysiology is reflected in the variable terms used to describe the entity as well as in the inconsistent definition of its location either as subdural or subgaleal. In the literature, they are often referred to as hygromas, external hydrocephalus, or extra-axial CSF accumulation.

In this study, we tried to distinguish between subgaleal CSF accumulations and subdural hygromas based on a definable dural layer on the postoperative CT scan, assuming that subgaleal CSF accumulation is the more decisive factor regarding wound healing problems. This was not always possible since both subgaleal CSF accumulations and subdural hygromas occur on the ipsilateral side. It is also difficult to differentiate between their individual impacts on the increasing scalp flap tension and consecutive wound healing complications. Analysis of the postoperative CT scans showed a reduced occurrence of ipsilateral subgaleal CSF accumulation in the lumbar drainage group, which was associated with fewer wound healing events requiring revision surgery compared with the patients without lumbar drainage. Additionally, the reduced rate of wound healing problems and CSF fistula prevented wound infections and subdural empyema in the lumbar drainage group compared with the control group, whereas the overall rate of meningitis was similar. Thus, the risk for catheter-associated infection in the lumbar drainage group was low and might be outweighed by the reduced rate of bacterial intracranial infections following wound healing disorders and wound dehiscence.

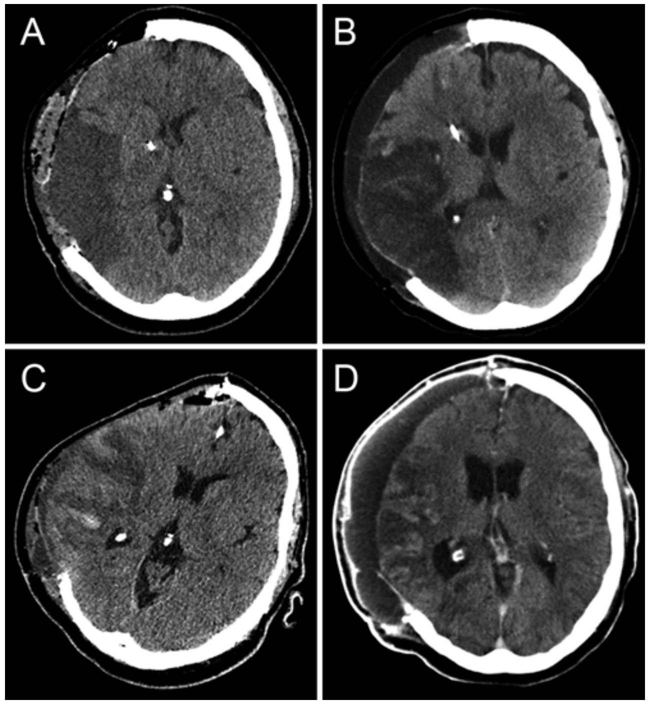


**FIG. 5.** Subdural hygroma and subgaleal CSF accumulation. **A and B:** CT scans obtained on the 1st (A) and 5th (B) postoperative days, showing subgaleal CSF accumulation in a 60-year-old female patient with MHS without lumbar drainage who had to undergo surgical wound revision. **C and D:** CT scans obtained on the 1st (C) and 17th (D) postoperative days, showing progressive hygroma in a 54-year-old male patient with MHS who underwent lumbar drainage and had to undergo revision with evacuation of the hygroma because of mass effect.

However, there was a higher proportion of patients with postoperative hygromas in the lumbar drainage group. At the same time, hygromas seemed to arise more often in different areas such as interhemispheric or contralateral locations. This might be due to an increased intracranial hypotension caused by the lumbar drainage. In some cases, the width of the hygromas might increase in the lumbar drainage group, causing additional mass effect on the brain with consequent external brain tamponade. In fact, even though the median width of the hygromas was the same, 2 patients in the lumbar drainage group had to undergo revision surgery with evacuation of a hygroma because of increased mass effect with neurological deterioration. Therefore, patients with lumbar drainage need to be monitored more intensively to detect early neurological deterioration, which might not only be caused by progressive hygroma but also by paradoxical herniation.

## Paradoxical Herniation

Paradoxical herniation is one the most feared and potentially fatal complications after lumbar puncture or CSF drainage in the presence of DHC.[26] While external brain tamponade results from brain swelling with increased mass effect, paradoxical herniation is thought to be a consequence of declining brain swelling and atmospheric pressure exceeding intracranial pressure.[27] Once the skull is removed, the cranium is converted from a closed to an open box, and atmospheric pressure exerts additional downward forces on the brain. Under this condition, CSF drainage increases the pressure gradient between the cranial and the spinal compartment and might lead to a herniation syndrome with rapid neurological deterioration.[8] The risk increases when the initial pathology or brain swelling resolves and ICP decreases. Hence, the risk of paradoxical herniation provoked by CSF drainage seems to be low early after surgery when edema and brain swelling is at their peak.

In our study, lumbar CSF drainage caused paradoxical herniation in 1 patient 5 days after lumbar drainage was initiated. At the time neurological deterioration began, brain swelling declined, and the scalp flap was no longer tense and started to sink. After lumbar drainage was discontinued and a blood patch was performed, the patient's neurological status rapidly improved and clinical signs of herniation resolved completely. The patient survived with only moderate deficits related to the primary disease and presented at a long-term outcome with a favorable mRS score of 3. With the exception of this patient, all other patients presented with a bulged skin flap. Furthermore, prior to the CSF drainage, the status of the basal cisterns was assessed on the CT scan obtained on the 1st postoperative day, since previous studies demonstrated a statistical correlation between absent basal cisterns on CT scans after lumbar CSF drainage and a worse clinical outcome.[28] Only if the basal cisterns were open was 5 ml CSF drained every hour. Under those circumstances, no other patient experienced paradoxical herniation in the drainage group, and radiological studies did not reveal a higher rate of transtentorial or tonsillar herniation signs identified on the consecutive postoperative CT scans.

Therefore, the often-postulated risk for paradoxical herniation might be overestimated early after DHC. The risk is especially low if lumbar CSF drainage is interrupted when the difference between the ICP and the lumbar pressure measured with the pressure transducer positioned at the level of the external acoustic meatus is more than 5 mm Hg. Simultaneous intracranial and lumbar pressure monitoring has been demonstrated to be a useful tool in avoiding overdrainge.[29] Our results are in agreement with the findings by Creutzfeldt et al. that confirmed a very low risk for paradoxical herniation within the 1st month after DHC.[30] However, a case report by Wang et al. demonstrated that in rare cases, early postoperative timing of lumbar drainage and a bulged skin flap do not provide absolute protection.[31] Therefore, patients need to be monitored more intensively for early neurological deterioration and symptoms of sinking skin flap syndrome.

### Placement of a Lumbar Drain Instead of an EVD

In patients who need to undergo DHC, the placement of an EVD is often impeded by the compression and lateralization of the ventricles due to swelling and midline shift. Especially in patients with MHS, which accounted for almost two-thirds of the patients in our study, placement of an EVD prior to surgery is not necessary and entails a higher risk for malposition and hemorrhagic complications because of the vulnerability of the infarcted tissue when implanted intraoperatively. Instead, almost all patients received an intraparenchymal probe for ICP monitoring, and, therefore, the placement of a lumbar drainage is technically easier and safer than placing an additional EVD.

### Limitations

The retrospective and single-center design of our study is subject to several well-known limitations. First, we included a heterogeneous patient population, and potential confounders might be underestimated. Second, because of the retrospective nature of our study, results lack sufficient long-term follow-up data, including data on potentially delayed occurrence of paradoxical herniation caused by prolonged and occult CSF leakage. Therefore, no reliable conclusions regarding differences in outcome can be drawn. The median follow-up period of 12 days is too short to reveal any potential differences, and prospective studies are necessary to assess long-term effects and outcome. Third, in 6 patients, the surgeon decided not to implant an intracranial ICP monitoring probe since the swelling appeared to be compensated after DHC. In those patients, surveillance of the difference between ICP and lumbar pressure at the level of the external acoustic meatus for controlled lumbar CSF drainage was not possible. No drainage-associated complication or herniation was noted in these patients, however. For implementation of lumbar drainage after DHC, we recommend establishing intracranial ICP monitoring in every patient to ensure surveillance and safety. Unfortunately, we cannot provide ICP data on each of the groups retrospectively. Because of these limitations, especially the heterogeneity and patient number, the findings of our study should be interpreted with caution and need to be validated first. However, the results are promising and warrant future studies.

## Conclusions

Lumbar CSF drainage after decompressive hemicraniectomy may decrease subgaleal extra-axial CSF accumulation and leads to a significant and clinically relevant reduction of wound healing complications requiring revision surgery. Associated risks, including meningitis, overdrainage, and paradoxical herniation, proved to be low if the lumbar drainage is performed within the 1st postoperative week. Our results are promising and justify conducting a prospective controlled clinical trial.

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## Disclosures

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

## Author Contributions

Conception and design: Vajkoczy, Truckenmueller, Früh, Zdunczyk. Acquisition of data: Truckenmueller, Früh, Ahlborn. Analysis and interpretation of data: Truckenmueller, Früh, Wolf. Drafting the article: Truckenmueller, Früh. Critically revising the article: Vajkoczy, Truckenmueller, Früh, Wolf, Zdunczyk. Reviewed submitted version of manuscript: Vajkoczy, Truckenmueller, Früh, Wolf, Zdunczyk. Approved the final version of the manuscript on behalf of all authors: Vajkoczy. Statistical analysis: Truckenmueller, Früh. Administrative/technical/material support: Truckenmueller, Früh, Faust, Hecht, Onken. Study supervision: Vajkoczy, Truckenmueller, Früh, Zdunczyk.

## Supplemental Information

### Previous Presentations

Portions of this work were presented at the 73rd Annual Meeting of the German Society of Neurosurgery, Cologne, Germany, May 29–June 1, 2022.

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