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Cerebrospinal Fluid Diversion for Refractory Intracranial Hypertension in Traumatic Brain Injury: A Single Center Experience

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BACKGROUND: **Diversion of cerebrospinal fluid (CSF) is a common neurosurgical procedure for control of intracranial pressure (ICP) in the acute phase after traumatic brain injury (TBI), where medical management is insufficient. CSF can be drained via an external ventricular drain (EVD) or, in selected patients, via a lumbar (external lumbar drain [ELD]) drainage catheter. Considerable variability exists in neurosurgical practice on their use.**

METHODS: **A retrospective service evaluation was completed for patients receiving CSF diversion for ICP control after TBI, from April 2015 to August 2021. Patients were included whom fulfilled local criteria deeming them suitable for either ELD/EVD. Data were extracted from patient notes, including ICP values pre/postdrain insertion and safety data including infection or clinically/radiologically diagnosed tonsillar herniation.**

RESULTS: **Forty-one patients were retrospectively identified (ELD = 30 and EVD = 11). All patients had parenchymal ICP monitoring. Both modalities affected statistically significant decreases in ICP, with relative reductions at 1, 6, and 24 hour pre/postdrainage (at 24-hour ELD $P < 0.0001$, EVD $P < 0.01$). Similar rates of ICP control failure, blockage and leak occurred in both groups. A greater proportion of patients with EVD were treated for CSF infection than with ELD. One event of clinical tonsillar herniation is reported, which may have been in part attributable to ELD overdrainage, but which did not result in adverse outcome.**

CONCLUSIONS: **The data presented demonstrate that EVD and ELD can be successful in ICP control after TBI, with ELD limited to carefully selected patients with strict drainage protocols. The findings support prospective study to formally determine the relative risk-benefit profiles of CSF drainage modalities in TBI.**

INTRODUCTION

The acute management of moderate and severe traumatic brain injury (TBI) is directed at normalizing intracranial homeostasis. Whilst a number of variables can be monitored and targeted, current practices are principally aimed at avoidance of raised intracranial pressure (ICP) and maintenance of cerebral perfusion pressure.[1] ICP control is typically achieved through escalation of therapeutic intensity, with varying local protocols typically based on the Brain Trauma Foundation guidelines.[1] Medical management options for intracranial hypertension include sedation, mild hypocapnia, and

Key words
- Brain injuries
- Cerebrospinal fluid drainage
- Critical care
- Intracranial hypertension
- Neurosurgery
- Traumatic

Abbreviations and Acronyms

CNS: Central nervous system
CSF: Cerebrospinal fluid
CT: Computed tomography
ELD: External lumbar drain
EVD: External ventricular drain
GCS: Glasgow Coma Scale
ICP: Intracranial pressure
TBI: Traumatic brain injury
TIL: Therapeutic intensity level

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hyperosmolar therapy. Where further intervention is required beyond such measures, therapeutic options include diversion of cerebrospinal fluid (CSF), barbiturate coma, and decompressive craniectomy.

The physiological principle of CSF diversion to control ICP is understood in terms of the Monro-Kellie doctrine.[2,3] Diversion (or buffering) of 1 constituent of the intracranial compartment (CSF) permits increasing volume of other constituents (expanding hematoma or parenchymal edema in response to trauma), thereby mitigating increases of compartmental pressure. CSF diversion is established in contemporary neurosurgical practice *via* 2 modalities: 1) a ventriculostomy catheter in the lateral ventricle connected to an external ventricular drain (EVD) or 2) a lumbar catheter connected to an external lumbar drain (ELD) (for a carefully selected sub-set of patients). Once a drain modality is established, CSF drainage can be regulated through intermittent volume-controlled drainage, by continuous pressure-controlled drainage, or some combination thereof.[4] CSF diversion in TBI is more typically achieved *via* EVD, though there is considerable practice variation, with some centers utilizing ELD where deemed appropriate.[5] ELD originated as a method of reducing intraoperative cerebral tension,[6] but has since become established in a variety of surgical settings.[7-13]

One factor contributing to practice variability is due to the potential risk associated with ELD of iatrogenic transtentorial herniation, particularly where obliteration of the basal cisterns may create a pressure gradient between cranial and spinal CSF compartments; historical examples of herniation after lumbar puncture in patients with raised ICP illustrate the potential for this.[14-17] In other contexts of intracranial hypertension, the use of ELD has been successfully adopted, including in subarachnoid hemorrhage[18-20] and bacterial/cryptococcal meningitis.[21,22] In these contexts, ELD has been shown to achieve similar ICP control to ventriculostomy drainage without significant complication rates.

Whilst lumbar drainage and ventricular drainage both represent technical means of CSF diversion to achieve ICP control, EVD is typically favored. Lumbar drainage presents an alternative to ventriculostomy which avoids the passage of a drain through cerebral parenchyma. Whilst not well quantified in the literature, avoidance of siting a ventricular catheter may mitigate risks of ventriculitis, hemorrhage, or malposition.[23-25] Patients with TBI often have small lateral ventricles, which may render successful EVD positioning challenging or unachievable.

Recent systematic reviews of the literature of ELD in ICP control in patients with TBI demonstrated a paucity of evidence, but did not identify an unfavorable safety profile for lumbar drainage with specific patient selection and strict drainage protocols.[26,27] Careful selection criteria of patients for ELD based on computed tomography (CT) criteria, including patency of basal cisterns and absence of a surgical mass/cerebral herniation, have been utilized in previous studies.[18,28-33] Scoring systems based on such radiological features have been previously proposed for identification of patients where ELD is considered a safe means of drainage.[29]

Utilization of ELD for ICP control in TBI in recent years has prompted an increase in the research interest in the field.[18,28-33] There is a paucity of evidence on the efficacy and safety profile of ELD,[27] and no evidence in the literature which comparatively evaluates the 2 methods (EVD and ELD) or their relative advantages and disadvantages. As such, our objective is to evaluate the efficacy and safety of ELD and EVD in the control of refractory intracranial hypertension in acute TBI.

MATERIAL AND METHODS

We conducted a single center retrospective service evaluation of the safety and efficacy of ELD for control of intracranial hypertension in TBI. Patients admitted between April 2015 and August 2021 were included in the analysis.

Criteria for inclusion were, 1) patients aged over 16 years admitted to the intensive care unit for acute management of moderate or severe TBI, 2) requiring ICP monitoring (parenchymal monitoring in our center), and 3) requiring CSF diversion for uncontrolled intracranial hypertension (e.g., ICP of greater than 20 mmHg for more than 5 minutes despite maximal medical therapy). Exclusion criteria were, 1) patients with an alternative requirement for CSF diversion (high-volume intraventricular hemorrhage, nontraumatic etiology, entrapped ventricle, and posttraumatic hydrocephalus) or 2) patients receiving EVD insertion whom would have not met our strict criteria for lumbar drainage as per local practice guidelines (absence of significant supratentorial mass lesion or midline shift, discernible basal cisterns (see Manet and colleagues[31]), absence of posterior fossa mass lesion, no crowding at the foramen magnum, no tonsillar descent).

Data were collected on: patient demographics, length of intensive care unit stay, length of hospital stay; duration of ICP monitoring, duration of CSF diversion, ICP pre and postdrain siting, drainage volumes, and potential safety related events (clinical or radiological evidence of cerebral herniation, infection, blockage, need for revision, need for permanent CSF diversion, need for further ICP control surgery, and mortality). An incident of central nervous system (CNS) infection was defined as a patient receiving a course of antimicrobial therapy specifically with the intention of treating a suspected or confirmed CNS infection. Tonsillar position was assessed *via* CT head imaging with sagittal reconstruction, with the most inferior tonsillar position recorded with reference to the basion-opisthion (“McRae”) line.

Patients were identified through a prospectively recorded database of patients with ELD, and through identification by clinical coding of electronic records. Data were extracted via interrogation of electronic records.

For thorough retrospective review, all potential incidences of morbidity and mortality secondary to CSF diversion were discussed on 2 occasions: contemporaneously through established departmental adverse event monitoring, and retrospectively in January 2022 in the context of this retrospective single center experience. Retrospective review was performed by 2 senior neurosurgical consultants and 1 senior neurointensive care consultant with a subspecialty interest in neurotrauma, 2 neurosurgical registrars, and a senior neurotrauma clinical nurse specialist. The outcome of the review and discussion represents a consensus opinion on the potential contribution of ELD to adverse events.

Statistical analysis was performed using GraphPad Prism (9.2.0) (2021). Normality of data was tested with Shapiro-Wilk test, with nonparametric paired data tested with Wilcoxon matched pairs signed rank test. Binary logistic regression analysis was performed on the outcome of CNS infection based on the variables of ELD/EVD, age and duration of drainage. Mixed effects analysis was performed across pre- and post- CSF diversion CT scan derived tonsillar position values. Ethical approval was sought and granted by University Hospitals Birmingham audit department and registered under the local code of CARMS-15577.

RESULTS

Demographic Data

Between April 2015 and August 2021, 30 patients underwent lumbar drainage for ICP control after TBI. All received ICP monitoring via intraparenchymal catheter. The mean age of the patients was 39 years ±17 years. The mean initial Glasgow Coma Scale (GCS) score was 7 ± 4. Severe TBI was diagnosed in $n = 15$, moderate in $n = 10$ and initial GCS was not available in $n = 5$. During the same period 22 patients underwent ventricular drainage for ICP control after TBI, of these $n = 11$ were deemed retrospectively to have been suitable for lumbar drainage based on the highly selective criteria set out above. Reasons for exclusion were, absence of the basal cisterns (n = 8) and posterior fossa mass lesion (n = 3). The mean age of these patients was 54 years ±16 years. Mean initial GCS score was 8 ± 3. Initial GCS was not available in $n = 5$, severe TBI was diagnosed in $n = 3$, and moderate TBI in $n = 3$. Demographic details are summarized in Table 1. A CT Marshall Grade of 2 was predominant in both groups: n = 23 for ELD group and n = 7 for the EVD group. Of those with higher scores, n = 5 patients receiving ELD underwent other neurosurgical intervention prior to CSF diversion and n = 3 for EVD. On the CT scan performed prior to institution of CSF diversion, basal cisterns were discernible in all patients, with a degree of compression in n = 10 (ELD group) and n = 4 (EVD group).

Efficacy

ELD and EVD are effective at improving ICP control. At both 1 and 6 hours postinsertion, mean ICP across patients is within the normal range (Table 1). Figure 1 shows pre- and post-ELD insertion ICP values, matched to individual patients, demonstrating marked reduction in ICP values in the majority of patients, with 2 patients demonstrating an increase in ICP values despite drainage. ICP control is sustained over 24 hours. Figure 2 shows a strongly significant decrease in patients' ICP values in the 24-hour post-ELD insertion and a moderately significant decrease for patients with EVD.

Efficacy was further assessed based on change in 24 hours therapeutic intensity level (TIL) pre and postintroduction of CSF diversion measures. TIL scores were evaluated by fulfillment of criteria of the 38-point scoring system of intermediate TIL[34] (Figure 3).

Patient Selection - CT Criteria

Based on local CT criteria for suitability for ELD, compliance across 41 patients receiving ELD was 28/30. One patient received an ELD in the presence of midline shift of 11 mm. One further patient received an ELD after CT demonstrating 7 mm midline shift, but the procedure was performed as *ultima ratio* therapy as

Table 1. Participant Demographics

	ELD (n = 30)		EVD (n = 11)	
Parameter	Mean ± SD	Median	Mean ± SD	Median
Age (years)	38.9 ± 16.9	35	54.1 ± 15.7	60
Initial GCS score	7.5 ± 3.9	7	8.3 ± 2.9	8.5
Initial CT Marshall Score	2.4 ± 0.7	2	2.6 ± 1.3	2
ICU LOS (days)	20.1 ± 14.4	18	21.1 ± 3.8	20
Hospital LOS (days)	52.2 ± 75.8	38.5	55.9 ± 27.2	45
Duration from injury to drain insertion (days)	3.8 ± 2.3	4	3.4 ± 2.5	3
Duration from drain insertion to removal (days)	6.5 ± 3.5	6	10 ± 5.11	10
First 24 hour hourly drainage volume (ml)	8.4 ± 7.8	9	8.3 ± 7.2	6
ICP 1 hour before (mmHg)	22.6 ± 12.5	22	25 ± 7.8	23
ICP 1hour after (mmHg)	5.9 ± 5.6	5	10.9 ± 9.1	10
ICP 6 hours before (mmHg)	17.2 ± 7.5	17	20 ± 5	22
ICP 6 hours after (mmHg)	8.5 ± 4.4	8	12.2 ± 7.8	11.5

SD, Standard deviation; LOS, Length of Stay; ELD, External lumbar drain; EVD, External ventricular drain; GCS, Glasgow Coma Scale; CT, Computed tomography; ICU, Intensive care unit; ICP, Intracranial pressure.

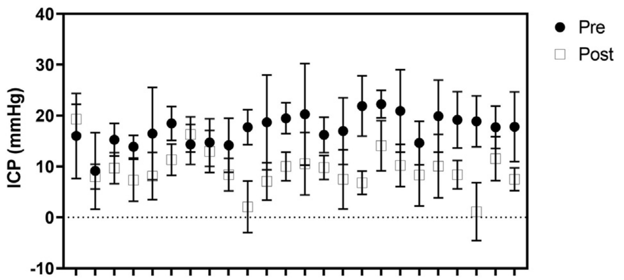


Figure 1. Matched pre- and post-external lumbar drain (ELD) insertion intracranial pressure (ICP) values. Matched ICP values for individual patients over 24 hours preceding (pre) and 24 hours following (post) ELD insertion.

not deemed suitable for further cranial surgery. All other patients with EVD or ELD met the CT criteria.

Patient Selection - ICP Criteria

For ELD, 29 of 30 patients fulfilled the local eligibility criteria of “ICP persistently raised between 20 and 35 despite best medical measures.” Eleven of 11 patients with EVD fulfilled these criteria. One of 30 patients received an ELD due to “elevated ICP >5 days postinjury resulting in inability to wean sedation.”

Drainage Protocol

Greater variability in the protocol for CSF drainage is noted in patients with ELD compared with EVD (**Table 2**). All patients had pressure-controlled drainage with EVD and 19/30 with ELD. Of these, 6 had volume limits prescribed (e.g., no greater than 10 ml/hr). Incidences of “overdrainage” (>20 ml in a single hour in the first 24 hours after insertion) were similar between ELD and EVD groups, with 4.7% and 4.8% of recorded drainage values over this threshold.

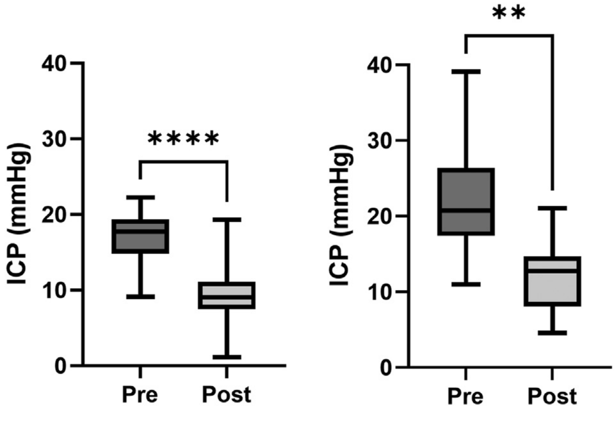


Figure 2. Combined data from pre- and post-ELD (left panel) or EVD (right panel) insertion ICP values from 24 hours preceding and immediately following drain insertion. Range, interquartile range, and median presented in each box plot. ** = $P < 0.01$; **** = $P < 0.0001$. ELD, External lumbar drain; ICP, Intracranial pressure; EVD, External ventricular drain.

Adverse Events

All cases of infection, blockage, or leak did not result in adverse neurological sequelae. Eleven cases of CSF diversion ended in mortality and/or subsequent ICP control surgery (ELD n = 7 [23%], EVD n = 4 [36%]) (**Table 3**). Due to clear differences between ELD and EVD groups, binary logistic regression analysis was performed on the outcome of CNS infection based on the variables of ELD/EVD, age and duration of drainage, but this trend was not statistically significant ($P = 0.46$).

For patients with ELD, 4 patients died within 1 month of injury. No case of mortality was attributable to the use of ELD determined by retrospective consensus discussion. One patient had a catastrophic injury from the outset and lumbar drainage had been instituted postdecompressive craniectomy as *ultima ratio* despite effaced basal cisterns and midline shift. One patient died from cardiac arrest secondary to propofol infusion syndrome. Two patients died after deterioration due to progression of unihemispheric TBI, despite decompressive craniectomy in one such case.

Three additional patients with ELD required subsequent surgical intervention for ICP control. Two were due to progression of unihemispheric TBI and the requirement for subsequent surgery was not deemed attributable to use of ELD. One patient developed uncontrollable intracranial hypertension and subsequently unreactive pupils (size 2) on day 6 postinjury and required decompressive craniectomy. Progression of TBI and tonsillar descent (6 mm) were present on a CT scan prior to decompressive surgery, and consensus opinion was that overdrainage via the ELD partially contributed to the noted tonsillar descent, in addition to progression of injury related swelling. The patient made a good neurological recovery with a Modified Rankin Scale score of 1 at 6 months postinjury.

For EVD, 1 patient died after withdrawal of care was deemed in the patient’s best interests, due to a poor neurological recovery in the context of underlying comorbidities. Three patients required decompressive surgery for refractory ICP despite EVD on the same day as EVD (n = 1), 1 day post-EVD (n = 1), and 5 days post-EVD (n = 1). All such cases were related to failure of EVD and medical therapies for achieving ICP control and were not deemed attributable to the use of an EVD.

To further evaluate the potential trends of tonsillar shift as a result of CSF diversion across both groups, CT images were analyzed for distance of cerebellar tonsils from the basion-opisthion (“McRae”) line (**Figure 4**). For all images, the most inferior tonsillar position was recorded, with tonsillar positions above the McRae line recorded as a negative value, and those below as a positive value. Patients were included where at least 1 CT head scan was performed during the CSF diversion period. Mixed-effects analysis with Geisser-Greenhouse correction between the 4 groups did not demonstrate any significant difference. Paired t tests between respective pre and postsubgroups for ELD and EVD also demonstrated no significant differences.

These findings were further analyzed by significant event analysis, where a significant event was determined by any postdrain value ≥3 mm (i.e. ≥3 mm below the foramen magnum). These significant events occurred in 28.6% of patients in both EVD and ELD groups. Using significant event criteria of any postdrain value ≥5 mm, n = 1 and n = 0 events occurred in ELD and EVD, respectively.

DISCUSSION

This retrospective observational data represent the first report of a comparative experience between EVD and ELD in TBI patients in the literature to date.[30] This preliminary comparison between ELD and EVD is limited in its methodology and power and as such any conclusions should be drawn with substantial caution, though it does demonstrate some similarities in efficacy and safety of the 2 modalities, within this selective sub-set of patients with TBI who met strict criteria of suitability for ELD. The present work further adds evidence to the efficacy and safety for CSF diversion as an adjunct for ICP control and represents a basis for more comprehensive prospective research.

Efficacy

The observed reductions in parenchymal ICP from 24 , 6 hours and 1 hour pre- and post-CSF diversion demonstrate similar efficacy across ELD and EVD. If "success" of CSF diversion is considered as the avoidance of more invasive neurosurgical ICP control procedures, the "success" rates of ELD and EVD are similarly favorable (>80%). Given our local procedure, where ELD is considered where maximal medical management of ICP fails, of 30 patients receiving ELD, 26 did not then require cranial surgery for ICP control. Similarly, 9 of 11 patients with EVD did not require more invasive ICP control measures.

Safety

Conclusively demonstrating safety for CSF diversion in TBI is challenging: potential complications of these procedures can be inextricable from the progression of the primary injury. In 30 cases here of ELD for ICP control in TBI, a single case was determined where ELD use was a potential contributing factor to an adverse event which did not result in adverse outcome. In this case, it was determined by multidisciplinary consensus panel that necessity for decompressive surgery is likely to have arisen in spite of ELD, but the urgency was potentially hastened by tonsillar descent, to which overdrainage by ELD may have contributed. This is in accordance with the literature which reports similar infrequent cases with the use of ELD.[20] Based on the results of this report, including the identification of high variability of drainage protocols, local practice has since been updated *via* a standard operating procedure to include a limit on midline shift (5 mm) and clear guidance on drainage protocols to include a volume drainage limit (initially 10 ml/hour). In our center's current practice (and in accordance with our current guidelines [Figure 5]), this patient would not be deemed suitable for ELD insertion and such levels of drainage would not be permitted. Cases such as this are evidence of the potential risk of ELD in ICP control for patients with TBI. However, factors such as patient selection and drainage protocols have a great effect on the safety of ELD, and in *strictly selected patients* with *strictly enacted protocols*, the use of ELD may avoid the need for EVD (or decompressive surgery) without undue additional risk burden to patients. Whilst this data do not offer sufficient power, in its numbers nor methodology, to draw conclusions on the noninferiority of ELD versus EVD, it may add support for further prospective study to this end.

The recorded rate of CNS infection in the EVD cohort reported here is higher than typically expected infection rates. There are some potential explanations, given the relative immunosuppressed state of trauma patients and, in particular, the older patient with neurological trauma. The higher age of the EVD cohort may in part explain this discrepancy, though this is also consistent with findings in the literature which have previously identified higher infection rates in EVD versus ELD.[23,24] The audit period encompasses a separate local quality improvement project which

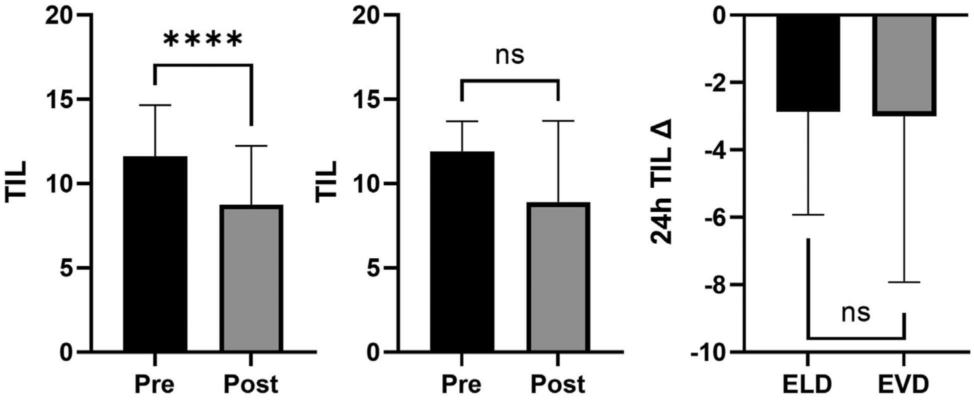


Figure 3. Left: Therapeutic intensity level (TIL) in 24 hours pre- and post-external lumbar drain (ELD) insertion. Middle: TIL in 24 hours pre- and post-external ventricular drain (EVD) insertion. Right: Comparison of change in 24 hours pre-/post-CSF diversion TIL in ELD and EVD groups. Error bars denote SD. **** = $P < 0.0001$. ns, non-significant; CSF, Cerebrospinal fluid.

Table 2. Initially Prescribed Drainage Protocol for Patients with ELD or EVD

	ELD (n = 30)	EVD (n = 11)
Pressure 5 cmH2O	1	0
Pressure 10 cmH2O	7	2
Pressure 12 cmH2O	1	1
Pressure 15 cmH2O	10	8
Pressure driven with volume limit	6	1
Volume 5 ml/hr	1	0
Volume 7.5 ml/hr	1	0
Volume 10 ml/hr	3	0
ICP dependent	1	0

ELD, External lumbar drain; EVD, External ventricular drain; ICP, Intracranial pressure.

has resulted in significant reductions in the infection rates of EVD in our center.[35] Comparative study of EVD versus ELD infection rates are limited and the small body of literature varies greatly, with evidence for similar rates,[36] and for reduced rates with ELD.[23,24] If an effect is present of higher infection rates in EVD, it may be attributable in part in this cohort to longer durations of drainage.[36] This effect may too explain the differences between need for long-term CSF diversion between groups, markedly greater in the EVD group. Again, the sample size is insufficient to draw conclusions in this regard, though the factors of ventricular catheter infection and extended duration of drainage may contribute to this observation.

Limitations

These data are limited by the retrospective design and by limited numbers of included patients. The retrospective case-control cohort design limits the validity of the findings of the comparative analysis, though groups are reasonably well matched by using strict criteria for allocation. Notably the age difference between groups should be considered. This (and the likely prevalence of other unrecorded differences) is inherent in groups, given the practice of a single unit was the basis for differing choice of CSF drainage modality. The authors recognize that the tendency to select ELD over EVD in our unit (which increased over the retrospective period) results in an inherent selection bias. Similarly, in patients rapidly developing intracranial hypertension, CSF diversion requiring EVD may be attempted to control ICP (prior to decompressive surgery) more readily in other centers. Given the greater age of the EVD cohort, the differing responses of CSF pathways in older age or the presence of low-volume intraventricular blood may have contemporaneously resulted in the choice of EVD where ELD would have been acceptable in accordance with local practice guidelines, but such nuance of decision-making is not discernible via retrospective study. However, it is felt that the methodology offers novel insights into the comparison of CSF diversion methods and is justifiable on this basis with a guarded approach to the interpretation of the findings.

The retrospective study design is a further limitation, particularly in the evaluation of adverse events and attribution of etiology on the basis of a retrospective case review. To mitigate this limitation, a multidisciplinary, multiexpert review panel was formed to consider each case of adverse outcome and considered radiological imaging, extensive clinical noting and monitoring data, as well as wider contemporaneous outcomes such as departmental morbidity findings. Due to the potential contribution of both disease progression and iatrogenic contribution to events such as tonsillar herniation, this approach was deemed the most valid for considering each case in the absence of any legitimate objective means of determining the relative contributions of injury or intervention. However it is inherently limited by its retrospective nature.

Table 3. Comparative Table of Complication/Event Rates in Patients with ELD and EVD

Complication/Event	ELD (%, Rate)	EVD (%, Rate)
Infection	10% (3/30)	45% (5/11)
Blockage	13% (4/30)	9% (1/11)
Blockage requiring revision	0% (0/30)	0% (0/11)
Drain system leakage	7% (2/30)	18% (2/11)
Long term CSF diversion	3% (1/30)	18% (2/11)
Failure of ICP control (i.e., subsequent surgical ICP intervention)	13% (4/30)	18% (2/11)
Mortality at 30 days	13% (4/30)	9% (1/11)

ELD, External lumbar drain; EVD, External ventricular drain; ICP, Intracranial pressure; CSF, Cerebrospinal fluid.

Comparative Synthesis

It is not possible based on the methodology or numbers included in the present cohort to draw conclusions on the relative merits or demerits of EVD and ELD as means of CSF diversion for ICP control in patients with TBI. However, it can be concluded that both methods are effective means of ICP control and result in significant reductions in ICP. ELD has been shown to correlate with a significant reduction in TIL in the 24 hours after commencing drainage. No episode of clinical tonsillar herniation was observed with use of EVD, in contrast to a single episode with ELD. This highlights the necessity for care in both patient selection and protocol implementation in the use of ELD. However, analysis of CT data did not demonstrate significant changes in tonsillar position in either group based on pre and postdrainage comparison of tonsillar position, and prevalence of radiological tonsillar descent via significant event analysis was the same in ELD and EVD groups. Trends of increased rates of infection and need for long-term CSF diversion after EVD require larger datasets and alternative methodology to validate. These observations support the need for comparative study of CSF diversion methods to fully elucidate the entire complication profile of the respective methods and inform future recommendations for method selection in clinical practice.

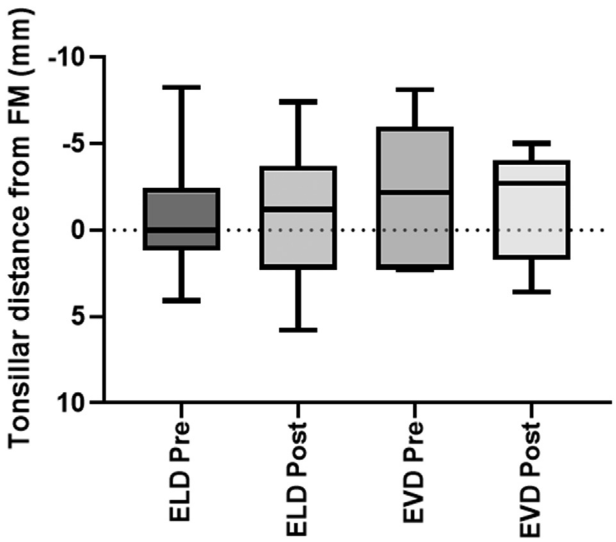


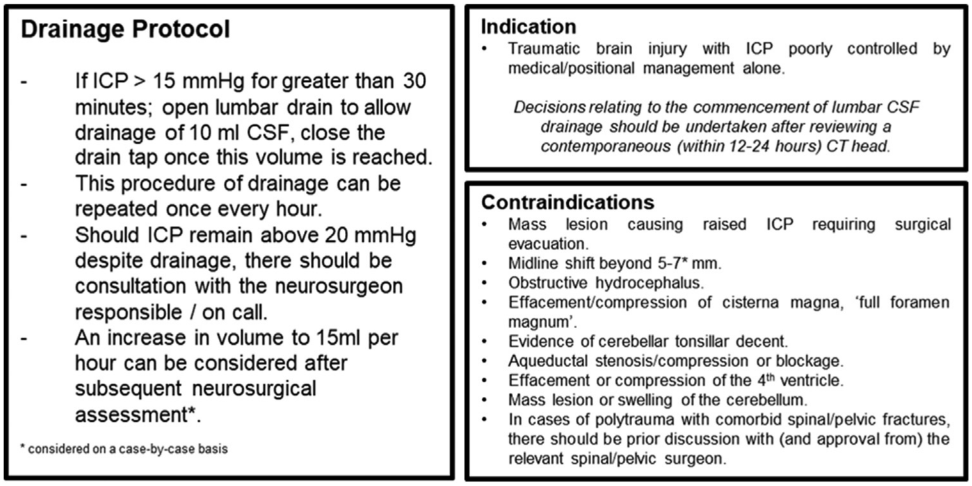
Figure 4. Box-and-whisker plot of tonsillar position relative to FM pre and postinsertion of lumbar (ELD) and ventricular (EVD) drains. Range, interquartile range and median presented in each box plot. No significant difference between groups was identified ($P > 0.05$). FM, foramen magnum; ELD, External lumbar drain; EVD, External ventricular drain.

CONCLUSIONS

These data add to a growing body of evidence concerning the efficacy and safety of CSF drainage methods for ICP control in TBI. Whilst this small number of patients reported from retrospective design cannot inform practice conclusively, it does support the notion that, in particular patients and under strict protocols, ELD and EVD can aid ICP control in medically refractory intracranial hypertension after TBI. The efficacy of ELD and EVD in reducing ICP in this particular group are similar and both statistically significant. Adverse event profiles are also similar with regard to blockage, leakage, and failure of ICP control. EVD may be associated with higher rates of CSF infection. One event of clinical tonsillar herniation is reported, which may have been attributable in part to ELD, but which did not result in adverse outcome, and highlights the absolute necessity for strict patient selection criteria and strict drainage protocols.

CRediT AUTHORSHIP CONTRIBUTION STATEMENT

Andrew R. Stevens: Conceptualization, Methodology, Data curation, Investigation, Formal analysis, Visualization, Writing — original draft, Project administration. **Helen Gilbody:** Data curation, Writing — review & editing. **Julian Greig:** Data curation, Writing — review & editing. **John Usuah:** Data curation, Writing — review & editing. **Basit Alagbe:** Data curation, Writing — review & editing. **Anne Preece:** Conceptualization, Data curation, Writing — review & editing. **Wai Cheong Soon:** Conceptualization, Data curation, Writing — review & editing. **Yasir A. Chowdhury:** Conceptualization, Data curation, Writing — review & editing. **Emma Toman:** Conceptualization, Data curation, Writing — review & editing. **Ramesh Chelvarajah:** Conceptualization, Validation, Supervision, Writing — review & editing. **Tonny Veenith:** Validation, Supervision, Writing — review & editing. **Antonio Belli:** Conceptualization, Validation, Supervision, Writing — review & editing. **David J. Davies:** Conceptualization, Validation, Supervision, Writing — review & editing.



Drainage Protocol

- If ICP > 15 mmHg for greater than 30 minutes; open lumbar drain to allow drainage of 10 ml CSF, close the drain tap once this volume is reached.
- This procedure of drainage can be repeated once every hour.
- Should ICP remain above 20 mmHg despite drainage, there should be consultation with the neurosurgeon responsible / on call.
- An increase in volume to 15ml per hour can be considered after subsequent neurosurgical assessment*.

* considered on a case-by-case basis

Indication

- Traumatic brain injury with ICP poorly controlled by medical/positional management alone.

Decisions relating to the commencement of lumbar CSF drainage should be undertaken after reviewing a contemporaneous (within 12-24 hours) CT head.

Contraindications

- Mass lesion causing raised ICP requiring surgical evacuation.
- Midline shift beyond 5-7* mm.
- Obstructive hydrocephalus.
- Effacement/compression of cisterna magna, 'full foramen magnum'.
- Evidence of cerebellar tonsillar decent.
- Aqueductal stenosis/compression or blockage.
- Effacement or compression of the 4th ventricle.
- Mass lesion or swelling of the cerebellum.
- In cases of polytrauma with comorbid spinal/pelvic fractures, there should be prior discussion with (and approval from) the relevant spinal/pelvic surgeon.

Figure 5. Standard operating procedure for ELD CSF diversion in TBI (instituted as a result of the present findings) at University Hospitals Birmingham, UK. ELD, External lumbar drain; CSF, Cerebrospinal fluid; TBI, Traumatic brain injury.

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