Journal of Clinical Neuroscience 81 (2020) 27–31

Contents lists available at ScienceDirect

Journal of Clinical Neuroscience

journal homepage: www.elsevier.com/locate/jocn

Clinical study

Accuracy of freehand external ventricular drain placement in patients after a large decompressive hemicraniectomy ☆

Cezar José Mizrahi [a,*,1], Iddo Paldor [b,1], Carlos Candanedo [c], Semira Mollica [a], Eyal Itshayek [d]

[a] Department of Neurosurgery, Royal Melbourne Hospital, University of Melbourne, Melbourne, Victoria, Australia
[b] Department of Neurosurgery, Rambam Health Care Campus, Haifa, Israel
[c] Department of Neurosurgery, Hadassah-Hebrew University Medical Center, Jerusalem, Israel
[d] Department of Neurosurgery, Rabin Medical Center, Petah Tikva, Israel

ARTICLE INFO

Article history:
Received 17 July 2020
Accepted 6 September 2020

Keywords:
Accuracy
Craniectomy
Decompressive craniectomy
External ventricular drain
Freehand

ABSTRACT

Our study aim is to evaluate the accuracy of freehand external ventricular drain (EVD) placement, without the use of adjuncts to placement, immediately following a large decompressive hemicraniectomy (DC). We performed a retrospective cohort analysis comparing patients who underwent freehand EVD placement immediately after a DC, to those who underwent freehand EVD placement without DC. Computed tomography (CT) studies were used to assess accuracy based on catheter tip location. Intracranial catheter length, pre- and post-operative Evan's Index, and midline shift pre- and post-operatively were analysed as separate variables in each group. A previously described grading system was used to assess the accuracy of free hand EVD placement. There were a total 110 patients overall; DC group, n = 50; non-DC group, n = 60. There was a significant reduction from pre-operative midline shift to post-operative midline shift in the DC group (9.13 vs 6.02 mm; $p = 0.0064$). There was no significant difference in accuracy between the two groups ($p = 0.8917$), and similar rates of Grade 1 – i.e. optimal – catheter tip location (DC = 78% vs non-DC = 81%) were found. All analysed variables comparing both Grade 1 subgroups (pre- and postoperative Evan's Index, and midline shift) showed significant differences between them. Mean catheter length in Grade 1 EVD placement showed a statistically significant difference between the DC and non-DC groups (63.78 vs 59.96 mm, respectively; $p = 0.009$). An EVD, after DC for traumatic and non-traumatic intracranial pathologies, can be accurately placed by freehand.

1. Introduction

External ventricular drain (EVD) insertion is one of the most common procedures in neurosurgery. They are the gold standard for monitoring intracranial pressure (ICP) and for draining cerebral spinal fluid (CSF), if needed. There are several adjuncts to EVD placement used in neurosurgical practice, including neuronavigation, ultrasound guidance and others.

Large decompressive hemicraniectomy (DC) is a life-saving procedure in patients with proven or suspected elevated ICP after traumatic brain injury (TBI), major ischemic stroke, and other intracranial pathology. DC has been proven to prevent cerebral herniation in different pathologies [1,2]. Following DC, ICP is often monitored, to verify lowering of the pressure. When an EVD is used for monitoring at the completion of DC, it is often placed without the use of adjuncts, in "freehand" form.

In the context of brain-shifting space-occupying lesions, whether traumatic or non-traumatic, the anatomy of the brain can be significantly distorted, even after DC for treatment of the brain-shift. Therefore, a freehand EVD carries a significant risk of inaccuracy.

Several studies have analysed the accuracy of a freehand EVD insertion [3–8]. However, there is a lack of high-quality data regarding the freehand insertion of EVDs in patients with intracranial distorted anatomy. In this study, we investigated the accuracy of freehand EVD placement in patients who have undergone large DC, compared to those who did not undergo large DC prior to EVD insertion.

☆ This material was presented as an oral presentation at the Israeli Neurosurgical Congress in Hertzliya, Israel, in March 2013.

* Corresponding author at: Department of Neurosurgery, The Royal Melbourne Hospital, 300 Grattan Street, Parkville 3050, Melbourne, VIC, Australia.

E-mail address: CezarJose.Mizrahi@mh.org.au (C.J. Mizrahi).

[1] Both Cezar José Mizrahi and Iddo Paldor contributed equally to this manuscript.

https://doi.org/10.1016/j.jocn.2020.09.003
0967-5868/

2. Methods

2.1. Participants and group selection

This is a retrospective analysis of all adult patients who underwent freehand EVD insertion, between February 2008 and September 2012. The data was retrospectively collected from the computerized database of the Hadassah Hebrew-University Medical Centre, a Level 1 Trauma Centre and a tertiary referral centre for neurosurgical patients in Jerusalem, Israel.

Patients who underwent EVD placement with assistance of neuronavigation, ultrasound or during intraventricular surgery were removed from analysis.

Patients who underwent freehand EVD insertion were then divided into two groups: 'DC group' and 'non-DC group'. The DC group consisted of those who underwent freehand EVD insertion immediately after a large decompressive hemicraniectomy. The non-DC group were those patients who underwent freehand EVD insertion without a large decompressive hemicraniectomy prior to EVD placement. Of a total of 110 patients who underwent freehand EVD placement, fifty patients were in the DC group, while sixty patients were in the non-DC group.

We included, in both groups, traumatic and non-traumatic intracranial pathologies. These included traumatic brain injury (TBI), rupture of intracranial aneurysms, spontaneous intraventricular haemorrhage, intraparenchymal spontaneous haemorrhages due to rupture of arteriovenous malformations (AVM), treatment of intracranial infection, and intracranial tumours. The baseline pathology, hospital course (before and after DC where relevant), and indication for EVD placement were noted and compared between the two groups.

Institutional Review Board (IRB# 0300-17-HMO) approval was obtained prior to the data collection. Informed consent was waived.

2.2. Outcome variables

The primary outcome of the study was to assess the accuracy of freehand EVD placement after DC, compared to patients who did not undergo DC prior to EVD placement. Images from post-operative computed tomography (CT) scans were used to assess catheter tip location. We also measured pre- and post-operative Evan's index, intracranial catheter length and midline shift (MLS) pre- and post-operatively.

Intracranial catheter length was measured from the EVD catheter tip to the inner table of the cranium at the site of the burr hole.

To assess ventricular size, the Evan's Index was used, which is the ratio between the maximal width of the bifrontal horns and the transverse inner diameter of the skull in the same CT level. For the purpose of this study, in patients after DC, the ratio was modified to the ratio between the maximal bifrontal ventricular width and the width from the inner table in one side and the outermost limit of the brain on the craniectomy side, due to the absence of the skull. An Evan's Index above 0.4–0.5 indicates enlarged ventricles, while a lower Evan's Index suggests non-hydrocephalic ventricles. An example of Evans index measurement – before and after DC – is shown in Figure 1.

2.3. EVD placement grading system

To evaluate the accuracy of EVD placement, a grading system first described by Karkala et al. [5] was used. Grade 1 represents optimal placement with the tip in the ipsilateral frontal horn, including passage to the third ventricle through Foramen of Monro. They defined grade 2 as functional placement into the contralateral lateral ventricle or into non-eloquent cortex. Grade 3 denotes sub-optimal placement into eloquent cortex, or non-target cerebrospinal fluid space, with or without functional drainage. The grading system we used, of EVD tip location, is presented in Figure 2.

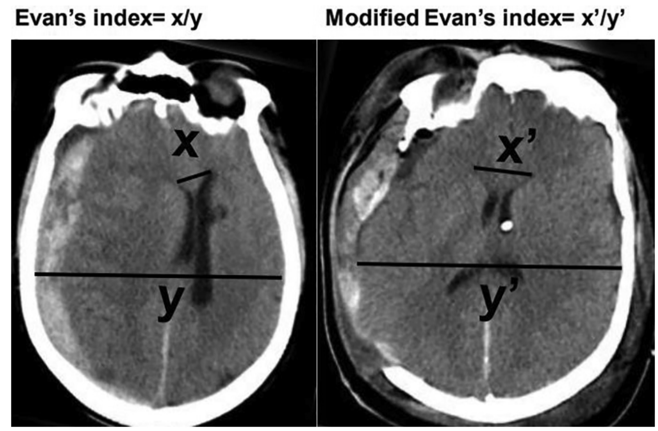

Fig. 1. Representative illustration of Evan's index and Modified Evan's index.

2.4. Procedure

The standard practice in our unit, in keeping with the Brain Trauma Foundation (BTF) Guidelines, is to perform a contralateral EVD insertion immediately following a large DC in the operating theatre. After routine skin preparation and draping, with the head in a neutral position, a 3 cm skin incision is made over Kocher's point (2.5 cm from the midline and 1 cm anterior to the coronal suture). A burr hole is made at this site using a pneumatic or manual drill. After opening the dura mater, a stylet-loaded ventricular catheter is introduced in a freehand technique, aiming towards the ipsilateral medial epicanthus in the coronal plane and just anterior to the external auditory meatus in the sagittal plane. The desired target is the ipsilateral anterior horn of the lateral ventricle close to the Foramen of Monro. The catheter is advanced no further than 7 cm from the brain surface. Free CSF outflow is considered indicative of a successful placement.

The indication for EVD placement in both groups was based on medical necessity. A CT scan is obtained after EVD insertion to assess the position of the EVD catheter and observe for post-procedural complications.

2.5. Statistical analysis

All continuous parameters are reported as the mean ± standard deviation. Unpaired t test was used to compare continuous data and χ^2 test was used to analyse non-continuous data.

Analyses was performed using GraphPad Prism version 7.0a (La Jolla, CA, USA). $p < 0.05$ was considered statistically significant.

2.6. Exclusion criteria

Patients under the age of 18 years old were excluded. Patients who preoperatively had intraparenchymal ICP monitor, and EVD or a ventricular shunt were not included in our analysis. We also did not include patients who had an EVD inserted under neuronavigation or ultrasound guidance. Finally, patients who underwent a DC 24 h or more prior to EVD insertion, or who had an EVD placed on the ipsilateral side to the craniectomy, were also excluded.

Grade	Accuracy of placement	Location of catheter tip
1	Optimal/adequate	Ipsilateral frontal horn, including tip of third ventricle
2	Suboptimal (shallow) in non-eloquent tissue	Contralateral frontal horn or lateral ventricle/corpus callosum/interhemispheric fissure
3	Suboptimal in eloquent tissue	Brainstem/cerebellum/internal capsule/basal ganglia/thalamus/occipital cortex/basal cisterns

Fig. 2. Grading system for catheter tip location (Karkala et al, 2008).

3. Results

3.1. DC group

Fifty patients underwent freehand placement of an EVD after a DC. Of the 50 patients, 35 patients (70%) were due to trauma, 9 (18%) to a major stroke, and 6 (12%) underwent the decompressive surgery due to rupture of an intracranial aneurysm.

3.2. Non-DC group

Sixty patients underwent freehand EVD placement without previous DC. Of these, 15 patients (25%) were due to primary hydrocephalus, 15 (25%) to trauma, 11 (18.3%) were associated with a ruptured intracranial aneurysm, 6 patients (10%) were from spontaneous intraventricular bleeding, 4 (6.7%) were for subsequent craniotomy for tumour resection, 4 (6.7%) were after intraparenchymal spontaneous bleeding due to a ruptured AVM, 3 (5%) were for treatment of an intracranial infection, 1 (1.7%) was for an intraventricular drug-infusion, and in one case (1.7%) the EVD was placed due to intraparenchymal bleeding after a tumour resection.

Variables and comparison inside each group are shown in Table 1.

3.3. Comparison between the two groups

3.3.1. Baseline parameters

Mean age was 49.12 ± 20 in the DC group and 47.45 ± 20 in the non-DC group, p = 0.6070. 74% of the patients were male in the DC group, and 57% were males in the non-DC group, p = 0.0585.

Preoperative Evan's index was 0.22 in the DC group, and 0.30 in the non-DC group. The degree of MLS was, as expected, different between both groups. MLS was 9.13 ± 0.77 in the DC group and 1.68 ± 0.63 in the non-DC group, p < 0.0001.

3.3.2. EVD and imaging outcomes in both groups

Grade 1 EVD placement was achieved in 78% of the patients in the DC group, and 81.7% in the non-DC group. Grade 2 placement was found in 12% and 10%, respectively and grade 3 was documented in 10.0% and 8.3%, respectively. These differences were not significant, p = 0.8917.

However, there was a significant difference in the catheter length between the DC group and non-DC group – 64.06 and 60.97 mm, respectively; p = 0.0276.

We continued to compare post-op parameters between patients in different placement grades. In patients who had Grade 1 EVD placement, there was a significant difference in catheter length between the DC and non-DC group (63.78 and 59.96 mm respectively; p = 0.009); There were also significant differences between the DC group and the non-DC group in post-operative Evan's Index (0.22 and 0.26, respectively; p = 0.0172) and in postoperative MLS (5.72 and 1.90 mm, respectively; p = 0.0014).

Table 1
DC group and Non-DC group by variables.

	DC Group (n = 50)	Non-DC group (n = 60)
EVD side placement		
Right	24 (48%)	40 (67%)
Left	26 (52%)	20 (33%)
Catheter length	64.06 ± 8.48 mm	60.97 ± 5.99 mm
Evan's Index		
Pre-operative	0.21 ± 0.04	0.30 ± 0.1
Post-operative	0.22 ± 0.05	0.27 ± 0.09
Pre- vs Post- operative Evan's index	p = 0.4971	p = 0.0512
Mean midline shift		
Pre-operative	9.13 ± 5.0 mm	2.20 ± 4.0 mm
Post-operative	6.02 ± 6.1 mm	2.13 ± 3.8 mm
Pre- vs Post-operative midline shift	$\mathbf{p = 0.0064}$	p = 0.9141

For Grade 2 EVD placement, possibly due to the small numbers, there were no significant differences in various parameters: catheter length was similar in the DC and non-DC group (61.05 and 61.93 mm, respectively; p = 0.7135). There were also no significant differences in pre-operative Evan's Index (0.24 and 0.32, respectively; p = 0.0755), pre-operative MLS (5.46 and 2.87 mm, respectively; p = 0.1866), post-operative Evan's Index (0.23 and 0.30, respectively; p = 0.053) and post-operative MLS (2.34 and 1.93 mm, respectively; p = 0.7870).

In Grade 3 EVD placements we found a significant difference between the DC and non-DC group for two parameters: pre-operative MLS (13.49 and 3.42 mm, respectively; p = 0.0043), and post-operative MLS (12.75 and 3.75 mm, respectively; p = 0.0158). However, there was no difference between the DC and non-DC groups for pre-operative Evan's Index (0.16 and 0.27, respectively; p = 0.0759); post-operative Evan's Index (0.18 and 0.24, respectively; p = 0.2217), and catheter length (69.94 and 64.15 mm, respectively; p = 0.5122)

Table 2 outlines the results between the two groups subdivided according to the EVD tip location grade.

Table 2
Comparison of the DC group and the non-DC group by demographics and broad variables.

	DC Group	Non-DC Group	*p value*
Patient Factors			
Age	49.12 ± 20	47.45 ± 20	0.6070
Gender			
Male	37 (74%)	34 (57%)	0.0585
Female	13 (26%)	26 (43%)	
Catheter length (mm)	64.06 ± 8.48	60.97 ± 5.99	**0.0276**
EVD Grade			
1	39 (78.0%)	49 (81.7%)	
2	6 (12.0%)	6 (10.0%)	0.8917
3	5 (10.0%)	5 (8.3%)	
Grade 1 EVD placement	***n = 39***	***n = 49***	
Catheter length (mm)	63.78 ± 0.94	59.96 ± 0.54	**0.009**
Evan's Index pre-op	0.22 ± 0.00	0.30 ± 0.01	**<0.0001**
Evan's Index post-op	0.22 ± 0.00	0.26 ± 0.01	**0.0172**
Midline shift pre-op (mm)	9.13 ± 0.77	1.68 ± 0.63	**<0.0001**
Midline shift post-op (mm)	5.72 ± 0.92	1.90 ± 0.66	**0.0014**
Grade 2 EVD placement	***n = 6***	***n = 6***	
Catheter length (mm)	61.05 ± 1.93	61.93 ± 1.2	0.7135
Evan's Index pre-op	0.24 ± 0.01	0.32 ± 0.02	0.0755
Evan's Index post-op	0.23 ± 0.01	0.30 ± 0.01	0.053
Midline shift pre-op (mm)	5.46 ± 1.36	2.87 ± 1.03	0.1866
Midline shift post-op (mm)	2.34 ± 0.67	1.93 ± 0.93	0.7870
Grade 3 EVD placement	***n = 5***	***n = 5***	
Catheter length (mm)	69.94 ± 9.63	64.15 ± 5.41	0.5856
Evan's Index pre-op	0.16 ± 0.01	0.27 ± 0.04	0.0759
Evan's Index post-op	0.18 ± 0.02	0.24 ± 0.04	0.2217
Midline shift pre-op (mm)	13.49 ± 2.22	3.42 ± 1.69	**0.0043**
Midline shift post-op (mm)	12.75 ± 3.34	3.75 ± 1.17	**0.0158**

4. Discussion

Several studies have analysed the safety and accuracy of EVD placement [5,7], ventricular catheters for ventricular-peritoneal shunts and Ommaya reservoirs [6,8]. However, none of these studies evaluated accuracy of EVD placement in patients who underwent a DC, where intracranial anatomy is severely distorted. The correct technique for EVD placement following DC is a day-to-day dilemma for the practicing neurosurgeon. The presumed distorted anatomy raises concern for misplacement with freehand technique, yet postoperative imaging and return to theatre for navigation-assisted EVD placement is labour-intensive and time-consuming. We believe the data presented here sheds light on some of the questions related to this dilemma.

First, the presumed distortion is well demonstrated by our pre-operative differences in MLS between the DC and non-DC groups.

The first rudimentary EVD was documented by Claude-Nicolas Le Cat (1700–1768) in October 1744 [9]. Since this time, there have been several advances on EVD placement [10–12]. Decompressive craniectomies have been historically considered a "rescue procedure" [13]. Several recent retrospective studies have shown that a significant percentage of patients experienced favourable outcomes after a decompressive craniectomy [14–18]. Jiang et al. [19] demonstrated in a large prospective randomized trial, that patients who underwent a 'limited' craniectomy had a higher percentage of poor functional outcomes compared to those who underwent a large DC. More recently, Rescue-ICP study [2] showed that patients after a DC had a more favourable mortality rate and functional outcome at 6, 12 and 18 months at follow up, when compared with those who received "maximal medical management" only, including barbiturate induced coma. Moreover, when correctly indicated, a DC can be a life-saving procedure in patients with intractable elevated ICP, in which placement of an EVD would be an urgent and useful tool.

Furthermore, our results demonstrate that patients in the DC group had some restoration of the anatomical distortion post-operatively, as demonstrated by the improvement of MLS (9.13 mm preoperatively vs 6.02 mm postoperatively; $p = 0.0064$). Although some restoration of the normal anatomy is reached, the MLS is not completely resolved, and a mean 6 mm MLS was documented postoperatively. This partial anatomical restoration may possibly increase the chance of successful freehand EVD placement.

Our study also demonstrated no significant difference in EVD tip location between the two groups ($p = 0.8917$). Grade 1 placement rates were similar between the DC and non-DC groups (78% vs 81%, respectively). When taking into consideration the variables (pre- and post-operative Evan's Index, and pre- and post-operative midline shift), our data showed a statistically significant difference between Grade 1 subgroups for DC and non-DC groups. These results suggest that despite the midline shift and the relatively smaller ventricles, freehand EVD placement after a DC is safe and reliable, and may be achieved adequately.

Lastly, catheter length in Grade 1 EVD placement showed a significant difference between the DC and non-DC groups (63.78 vs 59.96 mm, respectively; $p = 0.009$). This may indicate that due to the residual anatomy distortion in patients after a DC, a slightly deeper insertion of the catheter may be needed in order to achieve optimal EVD placement. However, further research with larger samples may be necessary to corroborate this theory.

The neurosurgical community is still continuing to investigate ways to improve the accuracy of EVD insertion with several advanced technological methods. Multiple studies have described new technologies with optimistic results [3,8,19–21], including one study using smart phone guidance [22]. Achieving useful imaging in patients immediately after a DC remains extremely challenging. This may be due to pre-operative imaging not reflecting the true anatomy after a DC. Therefore, repeat imaging should be required after a DC and before EVD insertion for new navigation reference, which puts patients at additional risk as it requires transfer to radiology and substantially increased operation time.

In conclusion, we believe that freehand EVD placement is a reliable and accurate in patients who have undergone DC and in those who have not. Both MLS and small ventricles, both found commonly in the emergent neurosurgical practice, do not affect the accuracy of freehand EVD placement.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Cooper DJ, Rosenfeld JV, Murray L, Arabi YM, Davies AR, D'Urso P, Kossmann T, Ponsford J, Seppelt I, Reilly P, Wolfe R. Decompressive craniectomy in diffuse traumatic brain injury. N Engl J Med 2011;364(16):1493–502.
[2] Hutchinson PJ, Kolias AG, Timofeev IS, Corteen EA, Czosnyka M, Timothy J, Anderson I, Bulters DO, Belli A, Eynon CA, Wadley J, Mendelow AD, Mitchell PM, Wilson MH, Critchley G, Sahuquillo J, Unterberg A, Servadei F, Teasdale GM, Pickard JD, Menon DK, Murray GD, Kirkpatrick PJ. Trial of decompressive craniectomy for traumatic intracranial hypertension. N Engl J Med 2016;375 (12):1119–30.
[3] Gautschi OP, Smoll NR, Kotowski M, Schatlo B, Tosic M, Stimec B, Fasel J, Schaller K, Bijlenga P. Non-assisted versus neuro-navigated and XperCT-guided external ventricular catheter placement: a comparative cadaver study. Acta Neurochir 2014;156(4):777–85. discussion 85.
[4] Huyette DR, Turnbow BJ, Kaufman C, Vaslow DF, Whiting BB, Oh MY. Accuracy of the freehand pass technique for ventriculostomy catheter placement: retrospective assessment using computed tomography scans. JNS 2008;108 (1):88–91.
[5] Kakarla UK, Kim LJ, Chang SW, Theodore N, Spetzler RF. Safety and accuracy of bedside external ventricular drain placement. Neurosurgery. 2008;63: ONS162-6; discussion ONS6-7.
[6] Lind CRP, Tsai AMC, Lind CJ, Law AJJ. Ventricular catheter placement accuracy in non-stereotactic shunt surgery for hydrocephalus. J Clin Neurosci 2009;16 (7):918–20.
[7] Oleary ST, Kole MK, Hoover DA, Hysell SE, Thomas A, Shaffrey CI. Efficacy of the Ghajar Guide revisited: a prospective study. J Neurosurg 2000;92:801–3.
[8] Wilson TJ, Stetler WR, Al-Holou WN, Sullivan SE. Comparison of the accuracy of ventricular catheter placement using freehand placement, ultrasonic guidance, and stereotactic neuronavigation: clinical article. J Neurosurg 2013;119 (1):66–70.
[9] Kompanje EJ, Delwel EJ. The first description of a device for repeated external ventricular drainage in the treatment of congenital hydrocephalus, invented in 1744 by Claude-Nicolas Le Cat. Pediatr Neurosurg 2003;39:10–3.
[10] Friedman WA, Vries JK. Percutaneous tunnel ventriculostomy. Summary of 100 procedures. J Neurosurg 1980;53:662–5.
[11] Saunders RL, Lyons TA. External ventricular drainage. A technical note. Crit Care Med 1979;7:556–8.
[12] Schultke E. Theodor Kocher's craniometer. Neurosurgery 2009;64:1001–4. discussion 4-5.
[13] Coplin WM, Cullen NK, Policherla PN, Vinas FC, Wilseck JM, Zafonte RD, Rengachary ASS. Safety and feasibility of craniectomy with duraplasty as the initial surgical intervention for severe traumatic brain injury. J Trauma 2001;50(6):1050–9.
[14] Aarabi B, Hesdorffer DC, Ahn ES, Aresco C, Scalea TM, Eisenberg HM. Outcome following decompressive craniectomy for malignant swelling due to severe head injury. J Neurosurg 2006;104(4):469–79.
[15] Albanèse J, Leone M, Alliez J-R, Kaya J-M, Antonini F, Alliez B, Martin C. Decompressive craniectomy for severe traumatic brain injury: evaluation of the effects at one year. Crit Care Med 2003;31(10):2535–8.
[16] Schneider GH, Bardt T, Lanksch WR, Unterberg A. Decompressive craniectomy following traumatic brain injury: ICP, CPP and neurological outcome. Acta Neurochir Suppl 2002;81:77–9.
[17] Soukiasian HJ, Hui T, Avital I, Eby J, Thompson R, Kleisli T, et al. Decompressive craniectomy in trauma patients with severe brain injury. Am Surg 2002;68:1066–71.

[18] Ucar T, Akyuz M, Kazan S, Tuncer R. Role of decompressive surgery in the management of severe head injuries: prognostic factors and patient selection. J Neurotrauma 2005;22(11):1311–8.
[19] Jiang J-Y, Xu W, Li W-P, Xu W-H, Zhang J, Bao Y-H, Ying Y-H, Luo Q-Z. Efficacy of standard trauma craniectomy for refractory intracranial hypertension with severe traumatic brain injury: a multicenter, prospective, randomized controlled study. J Neurotrauma 2005;22(6):623–8.
[20] Krotz M, Linsenmaier U, Kanz KG, Pfeifer KJ, Mutschler W, Reiser M. Evaluation of minimally invasive percutaneous CT-controlled ventriculostomy in patients with severe head trauma. Eur Radiol 2004;14(2):227–33.
[21] Mahan M, Spetzler RF, Nakaji P. Electromagnetic stereotactic navigation for external ventricular drain placement in the intensive care unit. J Clin Neurosci 2013;20(12):1718–22.
[22] Thomale UW. Intracranial ventricular catheter placement with a smartphone assisted instrument. Methods Mol Biol 2015;1256:405–17.