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Intracranial pressure changes in traumatic brain injury patients undergoing unilateral decompressive craniectomy with dural expansion

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ABSTRACT

Background: The aim of this study is to assess the ICP changes induced by a unilateral fronto-temporo-parietal DC with dural expansion after moderate to severe TBI. The effect of different bone flap sizes on ICP and the neurological outcomes were also evaluated after the decompressive surgery.
Methods: 52 TBI patients with clinical and radiological evidences of increased ICP were included in this prospective study. All patients received unilateral fronto-temporo-parietal DC with dural expansion and ventriculostomy at contralateral Kocher's point. Postoperatively, ICP values and the largest antero-posterior (AP) diameter of bone flap removed was measured, and the clinical outcomes were assessed using Extended Glasgow Outcome Scale (GOS-E) at discharge and 6 months after DC.
Results: The median ICP significantly decreased with an average of 56.7 % reduction from the initial opening ICP. Similar ICP changes were observed in all groups. This study also found that the large bone flap group (AP diameter >15 cm) demonstrated better postoperative ICP control as compared to the small bone flap group (AP diameter 12–15 cm), although not statistically significant. The SDH and cerebral swelling groups did better in the GOS-E at 6 months after TBI compared with cerebral contusion group.
Conclusion: The ICP reduction in moderate to severe TBI patients undergoing unilateral fronto-temporo-parietal DC with dural expansion occurred in accordance with decompressive steps, regardless of intracranial lesions and the surgical procedure should be performed with the bone flap size of at least 12 cm in AP diameter for adequate and sustained ICP control.

1. Introduction

Traumatic Brain Injury (TBI) is a major health care concern worldwide. About half of the patients who were hospitalized due severe TBI, either die or survive with severe permanent disabilities.[1,2] TBI can induce severe neurological damage owing to the primary and secondary insult leading to brain swelling, increased intracranial pressure (ICP), reduced cerebral perfusion pressure (CPP) and cerebral blood flow (CBF), inadequate oxygen delivery and ischemia. Increased ICP is common condition in severely injured brain and associated with high morbidity and mortality.[3–7] Refractory increased ICP, more than 20 mmHg, is a major prognosticator for poor neurological outcome and mortality.[5–8] ICP management is the cornerstone, although still controversial, in the treatment of TBI to ensure adequate CPP and CBF in order to prevent the undesirable sequelae such as ischemia and herniation. When the medical therapy fails to control the ICP, or when a mass lesion requires evacuation, surgical decompression has been a widely practiced management option. Decompressive Craniectomy (DC) with dural expansion is a surgical procedure in which portion of the cranial vault is removed and the dura mater is opened to increase the volume of intracranial compartment. It allows the swollen brain to have a controlled transcalvarial herniation while avoiding internal and

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brainstem compression. The additional intracranial volume shifts the pressure volume curve to the right and improve pressure volume-index, thus increasing the cerebral compliance.[9–12] These changes lead to reduction in ICP, increased in CPP and improvement in microvascular perfusion.

Conventionally, many neurosurgeons advocate "generous decompression" to accommodate the brain swelling, reduce the ICP and prevent the herniation. Brain Trauma Foundation currently recommends a large unilateral fronto-temporo-parietal DC, no smaller than 12 × 15 cm or 15 cm in diameter, for reduced mortality and improved neurologic outcomes in patients with TBI.[13] A retrospective study reported that DC with an antero-posterior (AP) diameter of less than 10 cm was associated with 100 % mortality.[14] There are limited publications on the exact size of bone flap removed during unilateral DC and the correlation between the bone flap size and the ICP reduction.

Although many studies have shown the advantageous effect of DC on ICP control,[3,6,9,15,16] however, little is known regarding the exact intraoperative ICP changes induced by DC. Therefore, the purposes of this study are: a) to assess the intraoperative and postoperative ICP changes induced by unilateral fronto-temporo-parietal DC with dural expansion; b) to evaluate the effect of different bone flap sizes on ICP changes; and c) to evaluate the neurological outcomes at discharge and 6 months after DC. In this study, we performed ventriculostomy and quantitatively measured the ICP values at each decompressive step during the unilateral DC and in the postoperative period. The largest AP diameter of bone flap was measured and recorded at the end of surgery. The neurological outcomes were assessed using Extended Glasgow Outcome Scale (GOS-E) scores at discharge and 6 months after DC.

2. Methods and materials

2.1. Research question

What is the pattern of ICP changes induced by unilateral DC in moderate and severe TBI patients and their neurological outcomes at 6 months post DC?

2.2. Patient population

Fifty-two moderate and severe TBI patients who underwent unilateral fronto-temporo-parietal DC with dural expansion were included in this prospective study. Approval to undertake the project was obtained from the Research and Ethics committee, Ministry of Health (MOH). (NMRR ID: NMRR-19-2544-50308). All patients received an initial cranial computed tomography (CT) scan as soon as possible at the time of presentation to emergency department or when the neurological deterioration was detected. The patients were categorised into 3 groups according to the primary lesions causing the mass effects – subdural hematoma (SDH), cerebral contusion and cerebral swelling. After the initial stabilisation, unilateral fronto-temporo-parietal DC with dural expansion was performed following consistent surgical indications. Postoperatively, all patients were admitted to ICU for ICP monitoring and standard medical therapy.

2.3. Inclusion and exclusion criteria

Inclusion criteria: 1) adult more than 18 years old; 2) radiological evidences of increased ICP on CT brain e.g. midline shift more than 5 mm and/or obliteration of basal cistern; 3) correlating neurological deterioration e.g. initial Glasgow Coma Scale (GCS) score equal or less than 8, worsening GCS score and/or dilated and unresponsive pupil to light and; 4) in patients on ICP monitoring, persistent ICP more than 20 mmHg despite maximal medical therapy with correlating radiological evidences of increased ICP on the CT brain; 5) standard unilateral fonto-temporo-parietal DC.

Exclusion criteria: 1) Patients with primary fatal brainstem failure, as indicated by persistent GCS score of 3 with no spontaneous respiration and/or bilateral fixed dilated pupils 2) Bilateral DC.

2.4. Surgical technique

In all patients, ventriculostomy was performed at the Kocher's point contralateral to the side of primary lesion prior to DC. A ventricular catheter was connected to pressure transducer for ICP monitoring during and after the decompressive surgery (Fig. 1). Unilateral fronto-temporo-parietal DC with dural expansion was then performed using large reverse "question mark" skin incision, 2 cm from midline, curving behind the parietal eminence and extending inferiorly to zygoma, about 1 cm anterior to tragus. The skin flap was reflected subperiosteally and pericranium graft flap was prepared for duraplasty. A large bone flap covering frontal, temporal and parietal lobe was removed. Additional bone was removed at the temporal region and flushed to the floor of the middle fossa (Fig. 2). Dural opening was performed over the entire region of bony decompression in a cruciate or stellate shape till about 1 cm from the edges of the craniectomy window. The underlying hematoma, if presence, was removed after the dural opening. Autologous duraplasty was completed using harvested pericranium graft flap. Subgaleal drain was inserted prior to skin closure. Muscle and skin were reapproximated using sutures. Cranioplasty was performed at 3–6 months after DC in surviving patients.

2.5. Postoperative management

After the surgery, all patients were admitted to ICU for ICP monitoring and medical therapy which includes sedation without muscle paralysis agent; ventilator support; osmotherapy using mannitol or hypertonic saline administration, draining of cerebrospinal fluid (CSF); and finally, thiopentone coma therapy (for those with stable vital signs) for the refractory increased ICP more than 20 mmHg (Fig. 3). CT brain was repeated within 24 h after surgery for reassessment. If clinically or radiologically indicated, ICP monitoring and medical therapy were prolonged in ICU.

2.6. Data collection

ICP was continuously monitored during and within 24 h after the decompression surgery. The highest sustained ICP values observed after

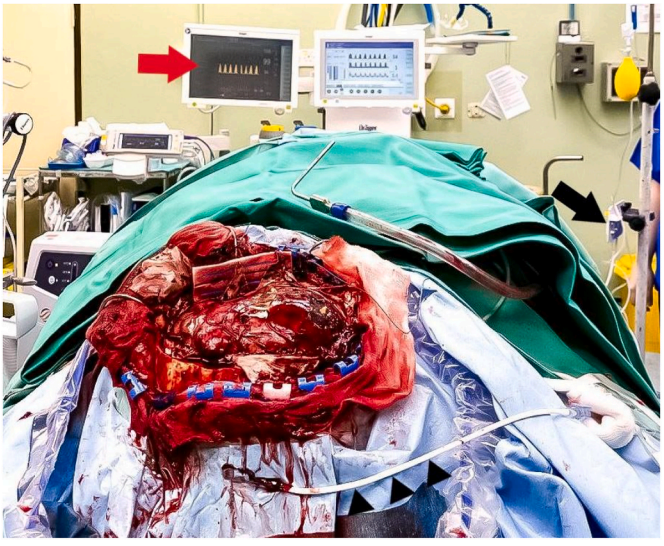

Fig. 1. Intraoperative ICP monitoring. The ventriculostomy was performed at the Kocher's point contralateral to the side of DC. Ventricular catheter (black arrow head) was connected to the pressure transducer (black arrow) for ICP monitoring (red arrow).

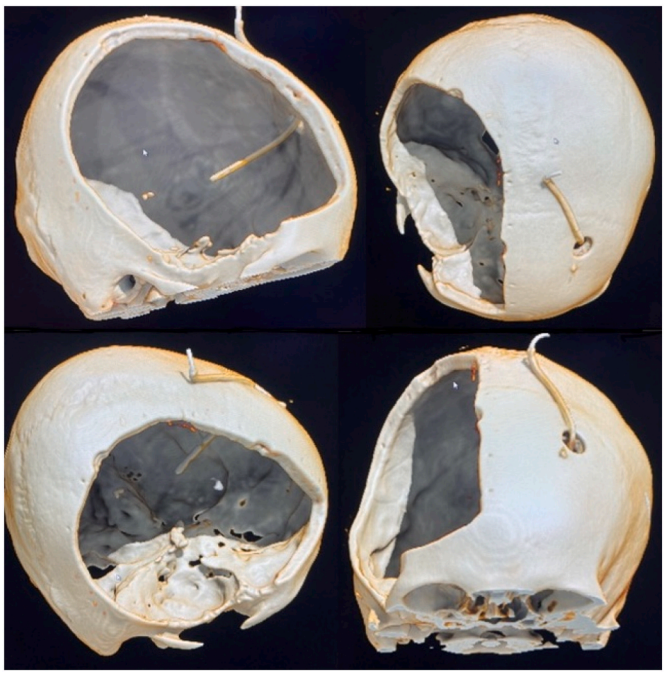

Fig. 2. 3D-reconstructed of brain CT following standard unilateral fronto-temporo-parietal DC.

ventriculostomy for 5–10 min was considered to be the opening ICP. In patient on ICP monitoring, the highest sustained ICP values prior to DC was considered as the opening ICP. The ICP values observed after removal of bone flap and dural opening were considered as craniectomy and durotomy ICP respectively. The ICP values obtained upon completion of skin closure, were considered as closing ICP. The ICP values were recorded again within 24 h in ICU. The largest AP diameter of the bone flap removed was measured at the end of decompressive surgery using a sterile ruler. The evaluation of the neurological outcomes was performed through a dichotomized Extended Glasgow Outcome Scale (GOS-E) at discharge and at 6 months after DC. The favourable outcome was defined as GOS-E of 5–8 and GOS-E of 1–4 were considered as unfavourable outcome.

Patients who fulfilled the selection criteria will have additional data collection form placed in their folder. Upon discharged, data collection form will be placed inside their follow-up folder and GOS-E score was filled during outpatient clinic follow-up. The completed data collection forms were collected by the primary investigator for analysis.

2.7. Statistical analysis

Data are presented as the mean ± SD and median (IQR) and compared using paired *T* test, one-way ANOVA and unpaired *T* test. The statistical analysis was computed using Statistical Package for Social Sciences (SPSS; IBM, Chicago, Illinois USA) version 26.0. The level of statistical significance was set at p-value <0.05.

3. Results

3.1. Demographic data of patients

A total of 52 patients were available for this prospective cohort analysis. There were 28 patients in SDH group, 17 patients in cerebral contusion group and 7 patients in cerebral swelling group. There were 41 males and 11 females, which equally distributed across all the groups (Table 1). The mean age of the recruited patients in the SDH group was 36, 40 for the cerebral contusion group and 31 for the cerebral swelling group. Other demographic characteristics were found to be insignificant for the preoperative GCS, Injury Severity Score (ISS), midline shift and appearance of basal cistern on preoperative CT.

3.2. ICP changes during unilateral DC with dural expansion

The median opening ICP was 30.0 (26.0–33.8) mmHg. After the removal of bone flap with intact dura, the ICP significantly decreased to 19.0 (26.0–33.8) mmHg (36.7 % of the opening ICP, p-value <0.001). After dural opening, the ICP further decreased to 12.0 (9.3–14.0) mmHg (23.3 % of the opening ICP, p-value <0.001). Finally, the closing ICP

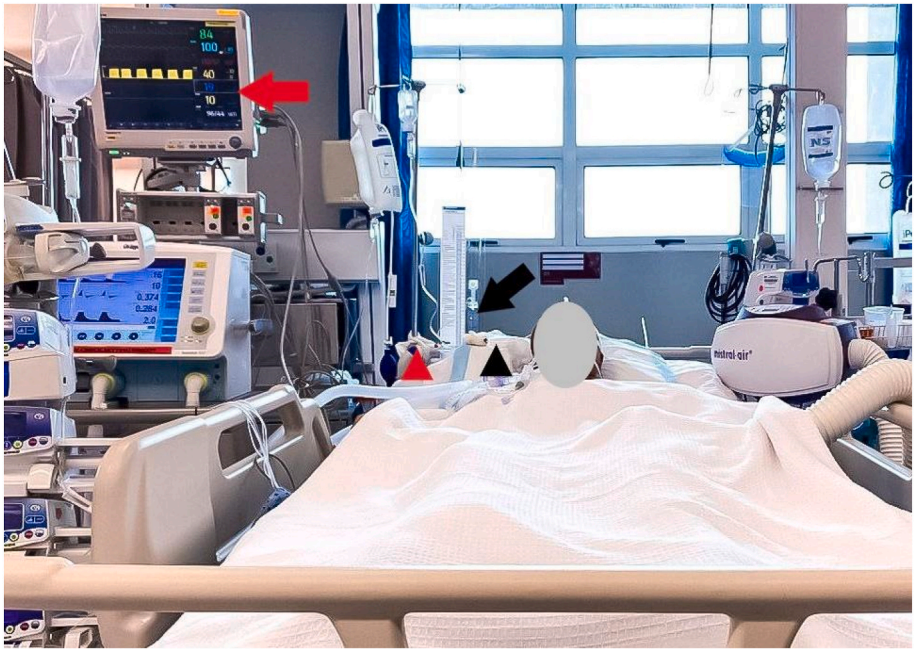

Fig. 3. Postoperative ICP monitoring and medical therapy in ICU. Ventricular catheter (black arrow head) was connected to the pressure transducer (red arrow head) for ICP and CPP monitoring (red arrow) and to the CSF chamber (black arrow) for CSF draining.

Table 1
Demographic characteristics of the patients.

	SDH	Cerebral Contusion	Cerebral swelling	*p*-value
Numbers (n)	28	17	7	
Age (years)	36.1	40.2	31.3	0.458
(±SD)	(16.67)	(16.32)	(14.91)	
Gender (n)				0.254
Male	22	15	4	
Female	6	2	3	
GCS score	7	7	7	0.675
(IQR)	(4.5–8.0)	(3.0–8.5)	(3.0–8.0)	
ISS	29	26	29	0.537
(IQR)	(26.0–32.2)	(25.0–33.5)	(25.0–33.0)	
Midline shift (mm)	8	7	7	0.577
(IQR)	(6.0–10.8)	(6.0–11.0)	(6.0–10.0)	
Basal cistern appearance (n)				0.316
Complete	20	10	3	
Partial	8	7	4	

recorded upon completion of the decompressive surgery was 13.0 (13.0–16.8) mmHg. Therefore, the overall ICP reduction observed following unilateral fronto-temporo-parietal DC with dural expansion was 56.7 % from the opening ICP (*p*-value <0.001). In the postoperative period, the median ICP gradually increased to 15.0 (13.0–16.8) mmHg within 24 h (Table 2). When we analysed the ICP changes according to the group, we observed similar ICP changes across all groups (Fig. 4).

3.3. Effect of bone flap size on ICP changes

The bone flap size ranged between 12.4 cm and 16.7 cm in AP diameter. We categorised the bone flap into large (more than 15 cm) and small (less than 15 cm) groups based on the Brain Trauma Foundation recommendation. There were 17 patients in large group and 35 patients in small group (Table 3). There was no statistical difference in the ICP changes in both groups. Higher median ICP values were recorded in postoperative period for small group as compared to large group but this was not statistically significant (*p*-value 0.069). In both groups, ICP control (<20 mmHg) was achieved immediately after decompressive surgery and sustained for 24 h in the postoperative period.

3.4. Clinical outcomes

There was no statistical difference in the length of ICU and hospital stay between the groups. Overall mortality was 19.2 % ($n = 10$). No mortality recorded in the cerebral swelling group but there were 6 (21.4 %) and 4 (23.5 %) patients died in SDH and cerebral contusion group respectively. At 6 months, 28 patients (53.2 %) had favourable outcome. The median GOS-E at discharge were similar in all groups. Better improvement in median GOS-E at 6 months were observed in SDH and cerebral swelling groups as compared to cerebral contusion group, however they are not statistically significant (*p*-value 0.065) (Table 4).

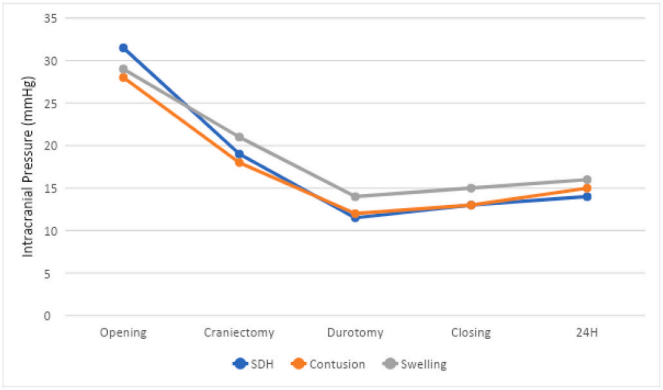

Fig. 4. Graph shows the pattern of ICP changes according to the decompressive steps during unilateral fronto-temporo-parietal DC with dural expansion.

Table 3
The median ICP (mmHg) changes according to bone flap size.

ICP (mmHg)	Large	Small	*p*-value
Numbers (n)	17	35	
Opening (IQR)	29.0 (26.5–34.5)	30.0 (26.0–33.0)	0.845
Craniectomy (IQR)	18.0 (16.0–21.0)	19.0 (16.0–23.0)	0.480
Durotomy (IQR)	11.0 (9.5–12.5)	12.0 (9.0–14.0)	0.189
Closing (IQR)	12.0 (9.5–15.0)	13.0 (11.0–15.0)	0.377
24H (IQR)	14.0 (12.0–16.0)	16.0 (14.0–17.0)	0.069

Table 4
Clinical outcomes according to the groups.

	SDH	Cerebral Contusion	Cerebral Swelling	*p*-value
Days of ICU stay (n) (IQR)	8 (6–13)	8 (5–12)	8 (7–10)	0.637
Days of Hospitalization (n) (IQR)	16 (13–39)	18 (14–40)	26 (15–45)	0.536
GOS-E at discharge (IQR)	3 (2–3)	2 (1.5–2.5)	3 (2–3)	0.180
GOS-E at 6 month (IQR)	5 (2–6)	2 (1.5–5)	5 (2–5)	0.065
Complications (n) (Expansion of contusion, Infection, Hydrocephalus, CSF fistula, Pulmonary Embolism)	9	8	2	0.608

Table 2
The median ICP (mmHg) changes observed during unilateral fronto-temporo-parietal DC with dural expansion.

ICP (mmHg)	Overall	SDH	Cerebral Contusion	Cerebral Swelling	*p*-value
Opening (IQR)	30.0 (26.0–33.8)	31.5 (26.0–35.0)	28.0 (26.0–32.0)	29.0 (28.0–33.0)	0.430
Craniectomy (IQR)	19.0 (16.0–22.0)	19.0 (16.0–20.0)	18.0 (16.5–24.0)	21.0 (16.0–23.0)	0.616
Durotomy (IQR)	12.0 (9.3–14.0)	11.5 (9.0–13.0)	12.0 (10.5–15.0)	14.0 (9.0–15.0)	0.397
Closing (IQR)	13.0 (11.0–15.0)	13.0 (10.3–14.8)	13.0 (11.0–16.0)	15.0 (11.0–18.0)	0.281
24H (IQR)	15.0 (13.0–16.8)	14.0 (12.0–16.8)	15.0 (14.0–16.5)	16.0 (15.0–17.0)	0.274

3.5. Adverse events and complications

Two patients (3.8 %) developed significant postoperative expansion of cerebral contusion requiring surgical evacuation. 9 patients (17.3 %) developed post-traumatic hydrocephalus and received ventriculoperitoneal shunt. Other surgical related complications included wound infection (9.6 %), CSF fistula (1.9 %) and pulmonary embolism (5.7 %).

In 9 patients who developed posttraumatic hydrocephalus, 6 patients (66.7 %) presented with GCS less than 5 prior to DC and 2 patients (28.6 %) had ventriculitis. All patients with post-traumatic hydrocephalus had unfavourable GOS-E score (less than 4) at discharge and 6-month.

4. Discussion

ICP management in TBI consists of medical and surgical modalities that usually follow a stepwise approach, with increasing aggressiveness according to the ICP values. Though regarded as the last-tier treatment for patients with refractory increased ICP, DC provides rapid and sustained control of ICP. Many previous studies have demonstrated that DC is an effective treatment strategy to alleviate persistent increased ICP in TBI.[3,6,9,15,16] The beneficial effect of DC on ICP in severely injured brain has been reported superior to medical therapy alone.[17–20]

In a meta-analysis published by E. Bor-Seng-Shu et al[3] in 2012, multiple studies looking at the ICP changes induced by DC were included with variable sample sizes from 5 to 100 participants. The surgical indications, age groups and good ICP control post operatively are similar with our study. Majority of the studies take 20 mmHg as ICP threshold for intervention. In our study, we included both primary and secondary DC as our sample population however most studies in the meta-analysis included mainly secondary DC. We focused on intra-operative ICP changes according to surgical steps in unilateral DC. The surgical technique varied between the studies in which some investigate on bilateral DC, unilateral DC and mixed unilateral and bilateral DC. Two other studies focus on ICP changes induced by DC in pediatric population.

4.1. ICP changes pre-, intra- and post-unilateral DC with dural expansion

In this study, the median ICP was significantly reduced from 30.0 (26.0–33.8) mmHg to 13.0 (1.0–15.0) mmHg, which accounts for 56.7 % reduction from opening ICP following unilateral DC with dural expansion. Aarabi et al,[16] Daboussi et al[6] and Howard et al[21] reported significant reduction of 39 % (23 (13–43) mmHg to 14 (2.9–29.7)) mmHg, 45 % (37 ± 17 mmHg to 20 ± 13 mm Hg) and 58 % (35.0 ± 13.5 mmHg to 14.6 ± 8.7 mmHg) from the initial ICP respectively following unilateral fronto-temporo-parietal DC. Several studies demonstrated that the postoperative ICP was the lowest immediately after DC and gradually increased over the next 24–48 h but remained stable and within the acceptable ICP range.[3,6,15,22] This is possibly due to progression of brain swelling, expansion of non-evacuated hematoma or development of delayed intracranial hematomas. In most cases, however, the additional intracranial volume induced by DC is adequate to accommodate the progression of injury. This postoperative ICP changes were also observed in this study, which the median ICP was 13.0 (11.0–15.0) mmHg immediately after DC and gradually increased to 15 (13.0–16.8) mmHg after 24 h. DC have also shown to decrease both the number and duration of high ICP episodes in postoperative period,[3,9] which can lead to less aggressive medical therapy and shorter ICU stays after the surgery.[18,23,24]

Intraoperatively, our data showed that the ICP reduction in unilateral DC with dural expansion occurred in accordance with decompressive steps. Craniectomy yielded higher ICP reduction compared with dural opening (36.7 % vs 23.3 % from initial ICP). Moringlane et al[25] studied the intraoperative ICP during unilateral DC in 18 patients with TBI and found that the ICP was strikingly 56 % lower after craniectomy and dural opening led to further 18 % reduction. However, in a retrospective analysis of bilateral DC for 37 patients with diffuse brain swelling following severe TBI, Bao et al[22] found that dural opening had a larger reduction than craniectomy (42 % vs 27 %). In another study, Kim et al[26] included both unilateral and bilateral DC in their analysis and found that craniectomy had higher reduction as compared to dural opening (49 % vs 30 %). It remains uncertain which of decompressive steps is superior to the other in achieving ICP reduction. However, both craniectomy and dural opening can lead to significant and sustained ICP reduction into the physiological ranges in severely injured brain. Brain is confined in two rigid structures – skull and a tough and thick membrane of dura mater. Skull is more rigid anatomy compared with dura mater. Therefore, craniectomy leads to higher ICP reduction than dural opening as shown in this study.

No significant difference in pre-, intra- and postoperative ICP changes were observed between the groups in our analysis. Verweij et al[27] reported the ICP before and during removal of acute SDH in five cases and found that craniectomy yielded a significant higher ICP reduction than dural opening with evacuation of hematoma. In a retrospective study in patients with cerebral contusion, the authors found that ICP was lowest after unilateral DC and then gradually increased over the next two to three days.[28] TBI is a diffuse intracranial injury with a complex pathophysiology resulting from the primary and secondary insult. Increased ICP in TBI can be contributed by several factors such as intracranial hematomas, cerebral oedema, hyperaemia secondary to vasomotor paralysis or loss of autoregulation, hypocarbia, hydrocephalus due to obstruction of CSF pathway or its absorption and increased intrathoracic or intraabdominal pressure.[29] However, a radiological study has suggested that cerebral oedema is the predominant factor for increased ICP in TBI.[30] This suggest that the increased ICP in TBI was largely contributed from the global insult rather than the focal hematoma alone, especially in the absence of sizeable hematoma.

4.2. Effect of different bone flap sizes on ICP changes

Despite being one of the commonest surgeries in neurosurgery, the optimal bone flap size in DC for ICP control remains unclear. Jiang et al[31] conducted RCT in 2005 and found a reduced mortality, increased good neurological outcomes and greater ICP reduction in patients who had treated with standard unilateral craniectomy (12 × 15 cm) when compared with patients underwent limited unilateral craniectomy (6 × 8 cm). In another RCT, the authors compared large unilateral fronto-temporo-parietal DC (15 cm in diameter) with small temporoparietal DC (8 cm in diameter) and found that large DC was associated with reduced mortality, improved neurological outcomes and better postoperative ICP control.[32] Reid et al[33] suggested that there is no direct correlation between the surface area of decompression and postoperative ICP. However, a recent study suggested that ICP is better controlled in patients who underwent unilateral DC with the craniectomy window more than 13.5 cm in diameter.[24] From our data, we found that both large (>15 cm) and small (<15 cm) groups led to significant ICP reduction immediately after DC. Although statistically not significant, we observed that the raising ICP trend in postoperative period was more stable in large group compared with small group. However, the postoperative ICP values remained less than 20 mmHg in both groups demonstrating adequate ICP control within 24 h after DC. In the small group, the size of bone flap ranged between 12 cm and 15 cm, which may explain why the ICP control following DC was comparable to the large group. During the surgery, we removed the bone following a few boundaries; anteriorly, 2 cm above the orbital ridges and to mid-pupillary line; posteriorly, 3–4 cm posterior to tragus and beyond parietal eminence; superiorly, 2–3 cm of the lateral edge of the superior sagital sinus; and inferiorly, floor of the middle cranial fossa at the origin of the zygomatic arch. Dura mater was opened over the entire craniectomy window to allow maximum expansion in a cruciate or stellate shape. However, we observed different bone flap sizes despite following the same boundaries. This is probably due to the anatomical variation in

which every patient has different cranial vault size. Taking this factor into account, therefore, the size of patient's head should also be taken into consideration when removing the bone flap during DC.

4.3. Clinical outcomes

The role of DC in the management of TBI remains a controversial subject, especially in the light of two RCTs on the subject. While the DECRA trial showed that DC was associated with unfavourable outcomes and no survival advantage, the more recently published RESCUEicp trial demonstrated that DC was associated with a better survival rate and neurological outcomes.[18,19] From our data, the overall mortality rate at 6 months is 19.2 % (10 deaths). Nine patients died within the same admission and only one more patient died at 6 months. This mortality rate is similar to those reported by Cooper et al[18] and Bao et al[22] with the mortality rates at 6 months of 19 % and 18.2 % respectively. In RESCUEicp trial,[19] the mortality rates at 6 months after surgery were 27 % but significantly lower when compared with medical group. Over the past two decades, the mortality rates have been improved with the reported rates ranged between 17% and 31 % with the decompressive surgery.[6,16,23,34–36]

For neurological outcomes, our data showed that moderate to severe TBI patients who underwent unilateral DC had overall 53.8 % ($n = 28$) favourable outcome at 6 months. In RESCUEicp trial, 42.8 % of patients had favourable outcome at 6 months compared with 34.6 % of patients in medical group.[19] While in DECRA trial, DC had only 30 % of favourable outcome at 6 months when compared with 49 % in standard care.[18] However, in RESCUEicp trial, the authors dichotomised upper severe disability (scale of 4) into favourable outcome while upper severe disability was included in unfavourable outcome in DECRA trial. Wettervik et al[34] reported that DC had 40 % favourable outcome using GOS-E score.

On further analysis, we found that 17 patients (32.7 %) were vegetative at discharge; but at 6 months post DC, only 10 patients (19.2 %) remained vegetative. This may suggest the potential benefit of DC in long-term follow-up. Between the groups, SDH and cerebral swelling groups exhibited more favourable outcome at 67.9 % and 57.1 % compared with cerebral contusion group at 35.3 % after 6 months. We also observed the higher number of vegetative patients ($n = 9$) in cerebral contusion group and majority remained vegetative after 6 months ($n = 6$). Huang et al[28] reported a better mean GOS-E score at 6 months in patients with haemorrhagic contusion who underwent DC without hematoma evacuation compared with craniotomy with hematoma evacuation, contusion debridement or lobectomy. In their study, the contusion was evacuated only when spontaneous rupture of the intraparenchymal haemorrhage to the cortical surface occurred during the operation or when persistent elevated ICP after DC. In contrast, we had tendency for evacuation of contused brain tissue appearing to be irreversibly damaged especially in sizeable hematomas. This may suggest the potential deleterious effect of evacuation of contused brain tissue in TBI that may affect the patient's neurological recovery. In our center, the accessibility to early inpatient and multidisciplinary rehabilitation service may contribute to patient's recovery and good clinical outcomes.

The median days of ICU and hospital stays in our study were 8 days (6–12) and 18 days (14–38). The length of ICU stay was similar across all groups however, the length of hospitalization was higher in cerebral swelling group. Cooper et al.[18] demonstrated that DC decreased the length of ICU stay with the median days of ICU stay was 13 days in DC group compared with 18 days in standard care group. An observational study found that the length of ICU stay in DC group was higher than the control group[36] while another study found no difference in means days of ICU stay in both groups.[23] Both RCTs reported decreased median days of hospitalization in DC group compared with control group.[18,19] However, Rubiano et al.[23] and Nirula et al.[36] found that DC increased the length of hospital stay. The reduced length of ICU stay after DC is likely to be attributed to a better ICP control in postoperative period which led to less aggressive medical therapy and early weaning. In our institution, ICP monitoring and medical therapy were usually discontinued 24 h after decompressive surgery unless the ICP was persistently high, more than 20 mmHg.

Repeated CT brain was done about 24 h after the completion of DC before discontinuing the medical therapy. No interval CT was performed unless there was clinical indication such as pupillary changes or uncontrolled intracranial hypertension.

4.4. Complications

DC is not without complications. In a large case series on surgical complications secondary to DC in TBI, they reported as much as 50 % of patients had at least one complication postoperatively.[37] Amongst common complications related to DC were herniation through craniectomy defect, subdural or subgaleal effusion, post traumatic hydrocephalus, syndrome of trephine, intracranial infection, CSF fistula and delayed intracranial hematoma on contralateral side.[16,28,37,38] In our studies, the highest number of DC related complications was post-traumatic hydrocephalus. However, the diagnosis of true hydrocephalus is always complicated.[39–41] Multiple risk factors were reported for the development of post-traumatic hydrocephalus such as DC, EVD placement, severity of TBI, traumatic subarachnoid hemorrhage, midline shift more than 5 mm and presence of subdural hygroma.[42,43] Post-traumatic hydrocephalus are usually associated with poor functional outcomes.[42,43] Most of our patients who developed post-traumatic hydrocephalus presented with GCS 3–5, had traumatic contusion and had unfavourable clinical outcome (GOS-E score <4). All of our patients who developed hydrocephalus received permanent ventriculoperitoneal shunt insertion. We also prefer to combine both cranioplasty and shunt insertion in the same surgery in order to avoid the syndrome of trephine after shunt insertion.

4.5. Limitations and recommendations

Although ICP is the main foundation in management of TBI, other parameters such as CPP, CBF, brain tissue oxygenation are equally paramount. Therefore, it is recommended that a retrospective study with a multivariate analysis looking at independent prognostic factors with larger sample size and include the above parameters.

Secondly, the sagittal height of the bone flap size cannot be accurately measured intraoperatively using a sterile ruler as part of the squama bone will be rongeured into small pieces in order to achieve adequate temporal decompression. We think the best method, to accurately measure the bone flap size and adequacy of temporal decompression, is to calculate area bone removed by comparing pre- and post-op CT brain.

Thirdly, we also recommend further analysis between secondary DC and medical standard care group, and between subgroup of severe TBI of GCS 3–5 and 5–8.

5. Conclusion

The ICP reduction in unilateral fronto-temporo-parietal DC with dural expansion occurred in accordance to decompressive steps. The craniectomy with intact dura yielded 36.7 % reduction from the opening ICP and the dural opening led to further 23.3 % reduction resulting in overall ICP reduction of 56.7 % upon completion of the decompressive surgery. For adequate and sustained ICP control, we suggest that unilateral fronto-temporo-parietal DC should be performed with the bone flap size of at least 12 cm in AP diameter and the dura mater is opened over the entire craniectomy window.

CRediT authorship contribution statement

Idris Shahrom: Writing – review & editing, Writing – original draft,

Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Saiful Azli Mat Nayan:** Writing – review & editing, Validation, Supervision, Project administration. **Jafri Malin Abdullah:** Supervision. **Abdul Rahman Izaini Ghani:** Supervision. **Nurul Firdausi Hasnol Basri:** Writing – review & editing. **Zamzuri Idris:** Supervision.

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.

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Abbreviation

AP –: Antero-posterior

CBF –: Cerebral Blood Flow
cm –: centimetre
CPP –: Cerebral Perfusion Pressure
CSF –: Cerebrospinal Fluid
CT –: Computed Tomography
DC –: Decompressive Craniectomy
GCS –: Glasgow Coma Score
GOS-E —: Extended Glasgow Outcome Scale
ICP –: Intracranial Pressure
ICU –: Intensive Care Unit
IQR –: Interquartile Range
ISS –: Injury Severity Scale
MLS –: Midline Shift
mm –: millimetre
mmHg –: Millimetre of Mercury
RCT –: Randomised Controlled Trial
SD –: Standard Deviation
SDH –: Subdural Hematoma
SPSS –: Statistical Package for Social Sciences
TBI –: Traumatic Brain Injury