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ORIGINAL ARTICLE

Intraoperative intracranial pressure and cerebral perfusion pressure for predicting surgical outcome in severe traumatic brain injury

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Abstract Intraoperative intracranial pressure (ICP) and cerebral perfusion pressure (CPP) were evaluated for use as prognostic indicators after surgery for severe traumatic brain injury (TBI), and threshold ICP and CPP values were determined to provide guidelines for patient management. This retrospective study reviewed data for 66 patients (20 females and 46 males) aged 13–83 years (average age, 48 years) who had received decompressive craniectomy and hematoma evacuation for severe TBI. The analysis of clinical characteristics included Glascow Coma Scale score, trauma mechanism, trauma severity, cerebral hemorrhage type, hematoma thickness observed on computed tomography scan, Glasgow Outcome Scale score, and mortality. Patients whose treatment included ICP monitoring had significantly better prognosis ($p < 0.001$) and significantly lower mortality ($p = 0.016$) compared to those who did not receive ICP monitoring. At all three major steps of the procedure, i.e., creation of the burr hole, evacuation of the hematoma, and closing of the wound, intraoperative ICP and CPP values significantly differed. The ICP and CPP values were also significantly associated with surgical outcome in the severe TBI patients. Between hematoma evacuation and wound closure, ICP and CPP values differed by 6.8 ± 4.5 and 6.5 ± 4.6 mmHg, respectively (mean difference, 6 mmHg). Intraoperative thresholds were 14 mmHg for ICP and 56mmH for CPP. Monitoring ICP and CPP during surgery improves management of severe TBI patients and provides an early

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prognostic indicator. During surgery for severe TBI, early detection of increased ICP is also crucial for enabling sufficiently early treatment to improve surgical outcome. However, further study is needed to determine the optimal intraoperative ICP and CPP thresholds before their use as subjective guidelines for managing severe TBI patients.

Introduction

Although severe traumatic brain injury (TBI) is the most common cause of death and long-term disability, optimizing the management of these patients is a continuing challenge. Insertion of an intracranial pressure (ICP) monitor has proven effective for improving surgical outcomes in severe TBI [1,2]. Although it has no therapeutic effect, the ICP monitor provides neurosurgeons with early and sufficiently precise information for detecting intracranial lesions. Information provided by ICP monitoring is also used in targeted therapies that are now standard treatment for severe TBI [3,4]. Introduction of the cerebral blood flow concept has led to development of targeted methods of treating severe TBI, including cerebral perfusion pressure (CPP) targeting [5–7] and modified CPP targeted therapies [8]. Because ICP targeted therapy, CPP targeted therapy, and modified CPP targeted therapy have proven effective for improving patient outcome after severe TBI [9], precise monitoring of ICP and CPP is essential when managing such patients. However, although ICP and CPP monitoring is standard postsurgery treatment for TBI, no studies have reported the use of ICP and CPP values monitored during surgery. A study of outcomes after surgery for severe TBI [10] showed that patients whose surgical treatment had included aggressive ICP monitoring had significantly better outcomes compared to patients who had not received ICP monitoring during surgery. Saul et al. [11] reported that early and aggressive treatment based on ICP monitoring significantly reduces the overall mortality rate of severe head injury. We therefore hypothesized that monitoring ICP and CPP during surgery improves subjective management of patients with severe TBI.

The objectives of this study were to evaluate the use of intraoperative ICP and CPP values as prognostic indicators and as subjective guidelines for managing severe TBI. Intraoperative ICP and CPP thresholds recommended for severe TBI were also determined.

Materials and methods

Patients

Out of 93 patients who had received surgery for severe TBI at the Neurosurgery Department of Chung-Ho Memorial Hospital, Kaohsiung Medical University from January 2006 to February 2007, this study analyzed the 66 patients who had received decompressive craniectomy with hematoma evacuation (20 females, 46 males; age range, 13–83 years; average age, 48 years). Of these 66 patients, the surgical treatment for 40 patients had included intraoperative ICP monitoring.

Inclusion criteria and exclusion criteria

The inclusion criteria were severe TBI defined as a Glasgow Coma Scale (GCS) score $\leq$8, unconscious status after resuscitation, surgical decompression, and ICP monitoring throughout the entire surgical procedure. Severe TBI was defined as a head injury with a GCS score $\leq$8. The clinical exclusion criteria were metabolic or drug-related unconscious status and prolonged ($>$30 minutes) shock status during surgery. None of the surviving patients that met the inclusion criteria was lost to follow-up after discharge.

Surgical technique

The CODMAN ICP Monitoring System (Codman ICP MicroSensor; Johnson & Johnson, Raynham, MA) measures intracranial pressure at the parenchymal level. When making the trauma flap, the burr hole was created along the path of the trauma flap and over the Kocher point to avoid the motor strip. The microsensor was inserted in the parenchyma. In patients who had received ICP monitoring throughout the procedure, the data analysis included ICP and CPP values after creation of the first burr hole, after hematoma evacuation, and after wound closure.

Data collection

The patient data included in this retrospective review included clinical characteristics, GCS score, trauma mechanism, abbreviated injury scale score (trauma severity), injury severity scale score, cerebral hemorrhage type, hematoma thickness on computed tomography (CT) scan, Glasgow Outcome Scale (GOS) score at 6 months after injury, and mortality defined as death within 1 month after surgery.

Statistical analysis

Patients whose surgical treatment had included ICP monitoring were compared by independent-sample t tests. Gender and mortality were compared by Chi-square test. The ICP (mmHg) and CPP (mmHg) values measured after creation of the first burr hole, after hematoma evacuation, and after wound closure were compared by paired t tests. The GOS scores were compared by Mann–Whitney U test. Groups A and B were compared by independent-sample t tests. The relationships between ICP and CPP values and GOS scores were evaluated by Spearman Correlation analysis. A p-value $<$0.05 was considered statistically significant. The Statistical Package for Social Sciences (SPSS) version 17.0 software was used for all statistical analyses.

Results

Table 1 compares clinical data between the severe TBI patients whose surgery had and had not included ICP monitoring. The comparisons of CT scans showed no significant differences in trauma mechanisms, trauma severity, cerebral hemorrhage type, or hematoma thickness. However, patients whose treatment included ICP monitoring had significantly ($p < 0.001$) better prognosis and significantly ($p = 0.016$) lower mortality.

Table 2 compares the ICP and CPP values after creation of the first burr hole, evacuation of the hematoma, and closure of the wound. The table also shows their correlations with GOS scores. Fig. 1 compares ICP and CPP values after creation of the first burr hole, after hematoma evacuation, and after wound closure. After hematoma evacuation, ICP and CPP were significantly lower and significantly higher, respectively, compared to their values after creation of the first burr hole ($p = 0.004$ and $p = 0.013$, respectively); after wound closure, ICP and CPP were significantly lower and significantly higher, respectively, compared to their values after hematoma evacuation ($p = 0.085$ and $p = 0.002$, respectively). Finally, after wound closure, ICP was significantly lower and CPP was significantly higher compared to their values after creation of the first burr hole ($p = 0.057$ and $p < 0.001$, respectively).

The differences in ICP between creation of the first burr hole and hematoma evacuation, between hematoma evacuation and wound closure, and between creation of the first burr hole and wound closure were 23.1 ± 8.0 mmHg, 6.8 ± 4.5 mmHg, and 16.3 ± 8.6 mmHg, respectively. The differences in CPP between creation of the first burr hole and hematoma evacuation, between hematoma evacuation and wound closure, and between creation of the first burr hole and wound closure were 20.9 ± 7.7 mmHg, 6.5 ± 4.6 mmHg, and 14.5 ± 8.3 mmHg, respectively. Comparisons of all ICP and CPP values after hematoma evacuation and after wound closure showed a mean difference of 6 mmHg. Between hematoma evacuation and wound closure, ICP and CPP differed by 6.8 ± 4.5 mmHg and 6.5 ± 4.6 mmHg, respectively (mean

Table 2 The relationship between the level of ICP and CPP, and the GOS in severe TBI.

Variable	r	*p*
Burr hole created		
ICP	−0.475	0.002*
CPP	+0.453	0.003*
Hematoma evacuation		
ICP	−0.473	<0.001*
CPP	+0.584	<0.001*
Wound closure		
ICP	−0.532	<0.001*
CPP	+0.720	<0.001*

*$p < 0.005$.
CPP = cerebral perfusion pressure; GOS = Glasgow Outcome Scale; ICP = intracranial pressure; r = Pearson correlation coefficient; TBI = traumatic brain injury.

Table 1 Comparison of clinical characteristics, mechanism and severity of brain injury, and outcome in patients with severe brain injury with and without ICP monitoring.

Variable	All patients ($n = 66$)	ICP monitoring ($n = 40$)	No ICP monitoring ($n = 26$)	*p*
Age (y)	48.5 ± 20.3	44.8 ± 21.3	54.2 ± 17.6	0.07
Sex (F/M)	20/46	15/25	5/21	0.12
Mechanism				
MVA	51	30	21	NA
Falls	12	8	4	NA
Firearm	3	2	1	NA
Severity of trauma				
AIS	6.4 ± 1.6	6.8 ± 1.8	5.9 ± 1.1	0.04*
ISS	27.1 ± 4.4	27.8 ± 5.0	26.2 ± 3.0	0.14
Severity of brain injury	5.3 ± 2.0	5.4 ± 1.9	5.2 ± 2.1	0.77
GCS				
Type of hematoma	50	35	15	NA
SDH	12	9	3	NA
EDH	42	27	15	NA
CH	34	22	12	NA
SAH	13.0 ± 6.4	12.6 ± 4.8	13.6 ± 8.4	0.54
Thickness (mm)	54/12	33/7	21/5	0.86
Midline shift (Y/N)				
GOS	2.8 ± 1.7	3.4 ± 1.7	1.8 ± 1.1	<0.001**
Mortality (Y/N, %)	25/66, 37.9%	11/40, 27.5%	14/26, 53.8%	0.007*

*$p < 0.05$; **$p < 0.005$.
AIS = Abbreviated Injury Scale; CH = contusion hematoma; EDH = epidural hematoma; GCS = Glasgow Coma Scale; GOS = Glasgow Outcome Scale; ISS = Injury Severity Score; MVA = motor vehicle accident; SAH = subarachnoid hematoma; SDH = subdural hematoma.

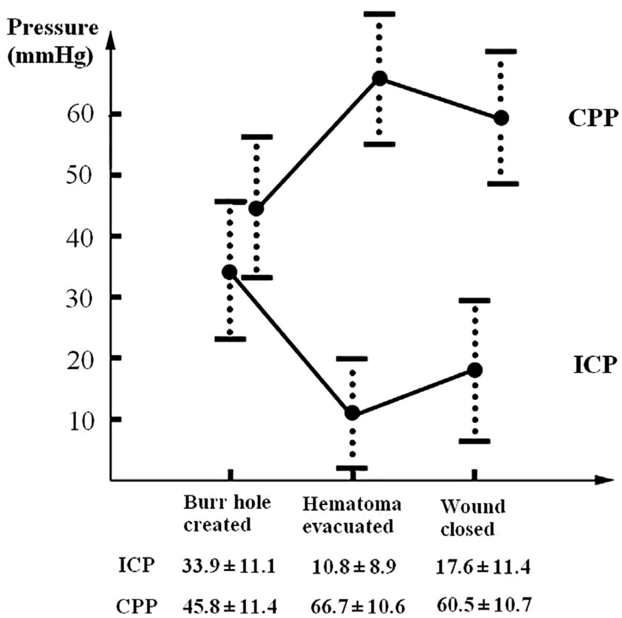

Figure 1. The levels of ICP and CPP when burr hole created, hematoma evacuated, and wound closed. CPP = cerebral perfusion pressure; ICP = intracranial pressure.

difference, 6 mmHg). Therefore, the proposed critical thresholds for ICP and CPP are 14 mmHg and 56 mmHg after hematoma evacuation, and 20 mmHg and 50 mmHg after wound closure, respectively. The patients were then grouped according to their critical ICP and CPP thresholds. Table 3 shows that in patients with ICP $<$ 14 mmHg or CPP $>$ 56 mmHg after hematoma evacuation and ICP $<$ 20 mmHg or CPP $>$ 50 mmHg after wound closure patients in Group A had better prognosis and lower mortality compared to those in Group B.

Discussion

Early and aggressive management of increased intracranial pressure can improve outcome and mortality in severe TBI [10,11]. Stein et al. showed that aggressive ICP monitoring during treatment for severe TBI is associated with significantly improved outcomes [10]. Saul et al. reported that early and aggressive treatment based on ICP values monitored during treatment significantly decreases the incidence of ICP of $\geq$25 mmHg and reduces the overall mortality rate of severe head injury [11]. In the current study, measurements of ICP and CPP values throughout the surgical procedure showed that ICP and CPP levels significantly differed among the three measurement points: after creation of the burr hole, after hematoma evacuation, and after wound closure. Monitoring ICP and CPP during surgery improves the subjective management of patients with severe TBI. Therefore, we recommend early ICP monitoring during targeted therapy to manage increases in intracranial hypertension and to improve overall functional outcomes in patients surgically treated for severe TBI.

Another benefit of intraoperative monitoring of ICP and CPP during surgery for severe TBI is in predicting outcome. A literature review shows that the main predictors of TBI surgery outcome are: age [12–15]; GCS on admission [13–16]; pupil response and size [13–16]; presence of hypoxia [13,16]; prolonged hypotension [16–18]; hyperthermia [13]; diffuse axonal injury [18] or brain stem injury

Table 3 Comparison of clinical characteristics, mechanism and severity of brain injury, and outcome in patients with severe brain injury between Groups A and B.

Variable	Group A (n = 26)	Group B (n = 14)	p
Age (years)	46.4 ± 21.6	41.7 ± 21.1	0.511
Sex (F/M)	9/17	6/8	0.608
Severity of trauma			
GCS	5.7 ± 2.0	4.8 ± 1.6	0.128
AIS	6.5 ± 1.4	7.1 ± 2.3	0.386
ISS	27.1 ± 4.9	29.1 ± 5.1	0.243
When first burr hole created			
ICP (mmHg)	29.4 ± 7.3	42.3 ± 12.4	0.002**
CPP (mmHg)	50.7 ± 7.2	36.8 ± 12.4	0.001**
When hematoma evacuated			
ICP (mmHg)	6.2 ± 2.9	19.4 ± 9.9	<0.001**
CPP (mmHg)	71.9 ± 5.6	57.9 ± 12.0	0.001**
When wound closed			
ICP (mmHg)	11.2 ± 3.6	29.5 ± 11.3	<0.001**
CPP (mmHg)	65.9 ± 5.7	50.2 ± 10.8	<0.001**
Day of ICP monitor inserted (day)	6.5 ± 2.7	5.9 ± 3.7	0.618
GOS	4.0 ± 1.3	2.4 ± 1.8	0.008*
Mortality(Y/N, %)	3/23, 12%	8/6, 57%	0.007*

*p < 0.05; **p < 0.005.
AIS = Abbreviated Injury Scale; CPP = cerebral perfusion pressure; GCS = Glasgow Coma Scale; GOS = Glasgow Outcome Scale; ICP = intracranial pressure; ISS = Injury Severity Score.

[17]; characteristic CT features [14—16]; and biomechanical parameters [19], including ICP, CPP, and partial pressure of oxygen in brain tissue. Low et al. [19] reported that the combined use of physiological and biochemical variables improves predictive accuracy. Although some prognostic models for predicting surgical outcomes in severe TBI have been validated [16,20—22], no prognostic model has used ICP and CPP values obtained during and after surgery. The current study showed that ICP and CPP values obtained during surgery for severe TBI are significantly associated with surgical outcomes. For predicting outcome and prognosis of surgery for severe TBI, we therefore recommend the use of ICP and CPP measurements taken either during surgery (i.e., after creation of the first burr hole and after evacuation of hematoma) and/or after surgery (i.e., after wound closure).

The 3rd edition of the *Guidelines for the Management of Severe Traumatic Brain Injury* (2007) recommends that surgery should be performed when the ICP threshold exceeds 20 mmHg [11,23—27] or when the CPP range is 50—70 mmHg. Surgery should be avoided when CPP is <50 mmHg [26—30]. No studies have proposed intraoperative thresholds for ICP and CPP during surgery for severe TBI. Based on the data obtained in this study, critical thresholds of 14 mmHg and 56 mmHg are proposed for ICP and CPP measured after hematoma evacuation, respectively, and critical thresholds of 20 mmHg and 50 mmHg are proposed for ICP and CPP measured after wound closure, respectively. In the patients whose treatment had included ICP and CPP monitoring in this study, those with ICP < 14 mmHg or CPP > 56 mmHg after hematoma evacuation and ICP < 20 mmHg or CPP > 50 mmHg after wound closure had significantly better prognosis and lower mortality compared to their counterparts. However, additional prospective, randomized, and controlled studies are needed to determine critical ICP and CPP thresholds after hematoma evacuation (during operation) and after wound closure (postoperation).

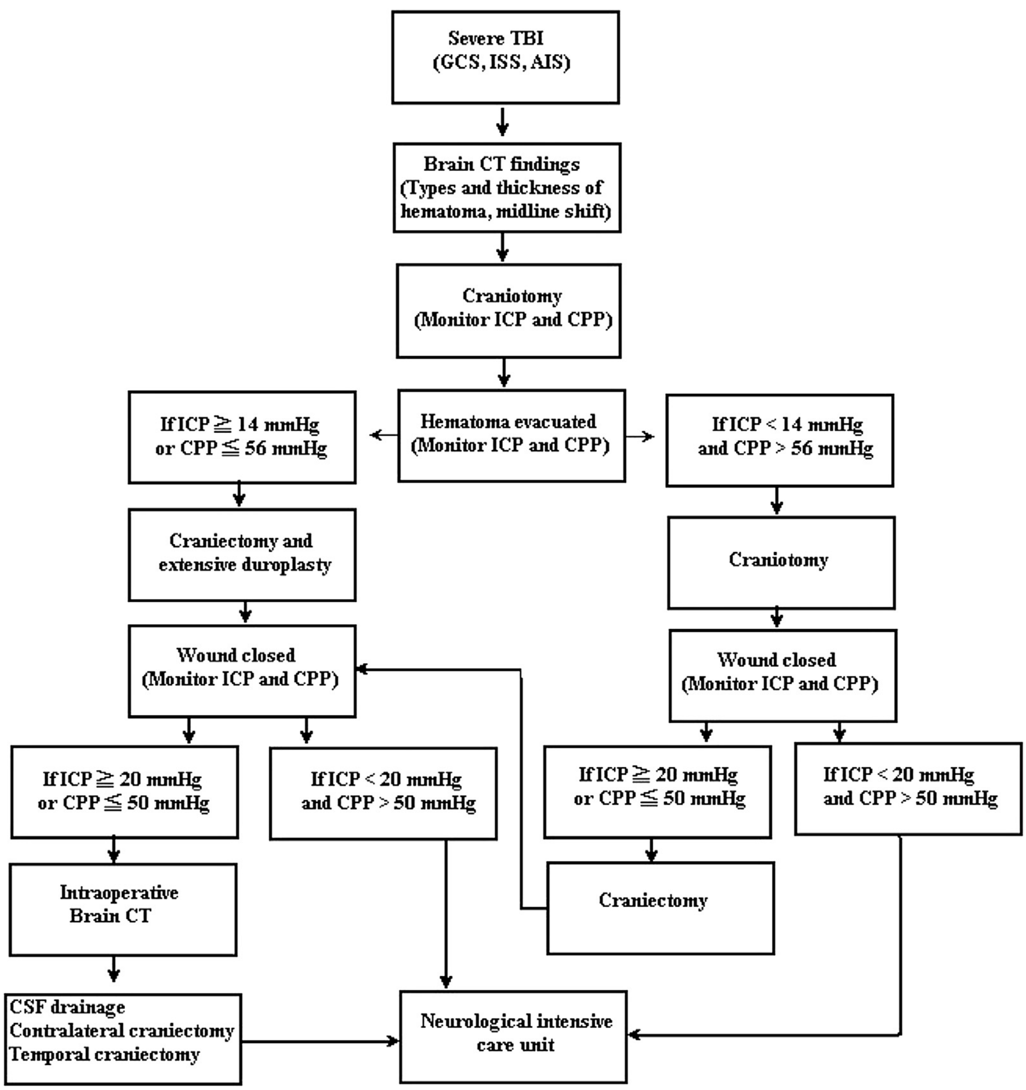

Figure 2. Algorithm for intraoperative management of severe TBI. AIS = Abbreviated Injury Scale; CPP = cerebral perfusion pressure; CSF = cerebrospinal fluid; CT = computed tomography; GCS = Glasgow Coma Scale; ICP = intracranial pressure; ISS = Injury Severity Score; TBI = traumatic brain injury.

Although new surgical techniques have contributed to improving surgical outcomes in severe TBI, a continuing patient management challenge is deciding whether and how decompression should be performed (i.e., by hematoma evacuation alone, by unilateral craniectomy, by bilateral craniectomy [3,31–36], or by internal uncinectomy combined with extensive duraplasty [37,38]). Monitoring ICP and CPP during surgery not only provides a subjective indicator that can be used for choosing the appropriate management in patients with severe TBI, it also provides data that can be used to detect intracranial lesions in further intraoperative image studies. Fig. 2 shows the recommended ICP and CPP thresholds obtained by the algorithm in this study for general management of severe TBI. During surgery, ICP should be $<$14 mmHg and CPP $>$ 56 mmHg; after wound closure, ICP should be $<$20 mmHg and CPP $>$ 50 mmHg. Targeted therapies should be performed during surgery. Hematoma evacuation should be performed only if ICP is $<$14 mmHg or if CPP is $>$56 mmHg. Craniectomy should be performed if ICP $\geq$ 20 mmHg or if CPP $\leq$ 50 mmHg after wound closure. Additionally, aggressive decompression, including extensive duraplasty, ventricular drainage, bilateral craniectomy, or internal uncinectomy, is required if ICP is $>$20 mmHg or if CPP is $<$50 mmHg before wound closure. Monitoring ICP and CPP provides a subjective indicator for determining whether decompression should be performed by hematoma evacuation alone, by unilateral or bilateral craniectomy, or by internal uncinectomy combined with extensive duraplasty. By providing an early indication of increased ICP, monitoring ICP during surgery can improve outcomes of surgery for severe TBI. Although monitoring ICP and CPP during surgery is vital for early detection of increases in ICP, one concern is managing refractory intracranial hypertension after completion of surgical evacuation. The diagnostic use of brain images obtained intraoperatively, including intraoperative CT, is feasible for use in early detection and management of refractory intracranial hypertension. However, the accuracy of intraoperative ICP and CPP measurements for predicting patient outcomes requires further evaluation in a larger series of prospective studies.

Conclusions

Monitoring ICP and CPP during surgery improves management in patients with severe TBI and provides an early prognostic indicator in such patients. Monitoring ICP during surgery can improve outcomes of surgery for severe TBI by providing an early indication of increased ICP. However, to provide subjective guideline for managing severe TBI, further studies are needed to determine the optimal intraoperative thresholds for ICP and CPP.

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