Clinical Factors Associated With ICU-Specific Care Following Supratentoral Brain Tumor Resection and Validation of a Risk Prediction Score

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Objectives: The postoperative management of patients who undergo brain tumor resection frequently occurs in an ICU. However, the routine admission of all patients to an ICU following surgery is controversial. This study seeks to identify the frequency with which patients undergoing elective supratentorial tumor resection require care, aside from frequent neurologic checks, that is specific to an ICU and to determine the frequency of new complications during ICU admission. Additionally, clinical predictors of ICU-specific care are identified, and a scoring system to discriminate patients most likely to require ICU-specific treatment is validated.

Design: Retrospective observational cohort study.

Setting: Academic neurosurgical center.

Patients: Two-hundred consecutive adult patients who underwent supratentorial brain tumor surgery. An additional 100 consecutive patients were used to validate the prediction score.

Interventions: None.

Measurements and Main Results: Univariate statistics and multivariable logistic regression were used to identify clinical characteristics associated with ICU-specific treatment. Eighteen patients (9%) received ICU-specific care, and 19 (9.5%) experienced new complications or underwent emergent imaging while in the ICU. Factors significantly associated with ICU-specific care included nonelective admission, preoperative Glasgow Coma Scale, and volume of IV fluids. A simple clinical scoring system that included Karnofsky Performance Status less than 70 (1 point), general endotracheal anesthesia (1 point), and any early postoperative complications (2 points) demonstrated excellent ability to discriminate patients who required ICU-specific care in both the derivation and validation cohorts.

Conclusions: Less than 10% of patients required ICU-specific care following supratentorial tumor resection. A simple clinical scoring system may aid clinicians in stratifying the risk of requiring ICU care and could inform triage decisions when ICU bed availability is limited. (*Crit Care Med* 2018; XX:00–00)

Key Words: craniotomy; intensive care unit; neurosurgery; postoperative care; supratentorial neoplasm

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Hospitals currently strive to provide quality care while effectively using limited resources (1–3). At many hospitals, ICU availability is frequently limited, which may result in declined transfers or cancelled surgeries (1, 4). It is routine practice for many institutions to admit all craniotomy patients to the ICU postoperatively regardless of a patient's surgical course or comorbidities (1, 5, 6). However, it has never been proven that routine postoperative ICU admission improves patient outcomes following craniotomies for tumor resection, and several authors have questioned this practice (7–10).

Unfortunately, there are limited recent studies to guide clinical decisions about postoperative ICU admission following brain tumor resection. Some authors have advocated that patients undergoing neurosurgical procedures receive postoperative care in a step-down unit or general care ward (1, 11–13) or even be discharged the same day after select procedures (14–16). However, the best way to identify patients most likely to tolerate this approach is unclear. A model to assist providers in stratifying the risk of receiving ICU level of care after supratentorial tumor surgery could assist with triage decisions. To our knowledge, a validated model has not previously been proposed.

We undertook this study in order to identify the rate of complications and the frequency of ICU-specific care in patients undergoing supratentorial tumor resection. We hypothesized that the rates of complications and ICU-specific care would be low. ICU-specific care was considered to be any intervention that must be delivered in an ICU at our institution. We further hypothesized that a relatively small number of patient and operative characteristics could be used to develop a model that discriminates patients who are most likely to require ICU-specific care

MATERIALS AND METHODS

Patient Population

We investigated complications and outcomes for 200 consecutive patients who underwent supratentorial brain tumor resection at a single academic medical center between March 2014 and August 2015. Patients were identified by querying billing records for current procedural terminology codes for supratentorial tumor resection (61510) and supratentorial meningioma resection (615120). Patients undergoing anterior and middle cranial fossae skull base resections were not included due to the inherent differences in surgical approaches and complication profiles for these procedures (1, 17–19). Patients whose final pathology did not reveal tumor were also excluded, as such patients were anticipated to have different clinical courses and complication rates. Additional exclusion criteria included age less than 18, infratentorial extension of tumor, endoscopic resection, or biopsy.

Study Design

This was a retrospective observational cohort study. The electronic medical record for each patient was reviewed by study authors. Using standard forms and definitions, patient data were abstracted. Operative complications were defined as any complications that occurred while the patient was physically located in the operating room (OR). Early postoperative complications were any complications that occurred after the patient left the OR for the postanesthetic care unit (PACU), for up to 4 hours. ICU complications were any complication that occurred after the patient left the PACU for the ICU or any complications occurring more than 4 hours after the patient left the OR. Since patients at our institution sometime have a prolonged PACU wait before an ICU bed becomes available, we considered any complications occurring more than 4 hours postoperatively to be an ICU complication, even if the patient was physically located in the PACU. This was done to avoid underestimating the number of ICU complications as a result of limited ICU bed availability.

ICU complications included symptomatic hematoma or pneumocephalus, ischemic stroke, seizure, unexpected new focal neurologic deficit, reintubation, return to the OR, acute respiratory failure, shock, acute coronary syndrome, and cardiac arrhythmias, as well as patients who received unexpected or emergent imaging studies for any reason. Unexpected new focal neurologic deficits were defined as new deficits that prompted imaging studies or intervention.

ICU-specific care was considered to be any intervention, other than hourly neurologic assessments that, by protocol, should be delivered in an ICU setting at our institution. Specifically, these include mechanical ventilation, noninvasive positive pressure ventilation (NIPPV) for respiratory failure, intracranial pressure (ICP) monitoring or external ventricular drainage (EVD), hypertonic fluid administration for cerebral edema, continuous infusion of vasoactive medications (vasopressors or antihypertensives), and management of status epilepticus.

All information was entered into a secure online research electronic data capture database (20). This study was approved by the Institutional Review Board at the University of Michigan.

Patient Care

All supratentorial tumor resections were performed by board-certified neurosurgeons. The majority of cases were performed by three surgeons with additional fellowship training in tumor neurosurgery (S.H-J., J.H., D.O.,). Following the procedure, patients are typically extubated in the OR and monitored in the PACU prior to transfer to the neurosurgical ICU (NICU). After admission to the NICU, standard of care includes the performance of neurologic checks every hour by trained nurses. MRI scans are usually obtained overnight. Patients receive postoperative steroids and seizure prophylaxis at the discretion of the attending neurosurgeon. After monitoring overnight, the patients are usually transferred to a general care floor the next morning, contingent on clinical stability and the absence of need for any ICU-specific interventions.

Statistical Methods

The clinical characteristics of patients who received ICU-specific interventions were compared with those who did not. Continuous variables were analyzed using *t* tests or the Wilcoxon rank-sum test, as appropriate. Categorical variables were assessed with chi-square or Fisher exact tests. Forward logistic regression, with an entry criteria of p value of less than 0.05, was used to select covariates for a final model. This model was then used to develop a single prediction score for likelihood of receiving ICU-specific care.

Performance of the prediction score was validated on a separate retrospective cohort of 100 consecutive patients undergoing supratentorial tumor resection between August 2015 and April 2016. Model discrimination was assessed using the area under the receiver operating curve method. Model calibration was tested using the Hosmer-Lemeshow goodness-of-fit test. Statistical significance was set at a two-sided alpha of less than 0.05. All analyses were performed using SAS version 9.4 (SAS

Institute, Cary, NC) and R Version 3.3.1 (R Foundation for Statistical Computing, Vienna, Austria).

RESULTS

Patient Demographics and Clinical Characteristics

Among the 200 patients in the derivation cohort, the average age was 53.6 years with 87 patients (43.5%) being female (**Table 1**). The most common tumor types were glioblastoma (29.0%) and metastasis (27.5%). An awake craniotomy was performed in 73 cases (36.5%), and intraoperative MRI was used in 48 cases (24.0%). The vast majority of patients (87.0%) were admitted to an ICU for less than 24 hours.

Intraoperative and Early Postoperative Complications

Intraoperatively, new focal neurologic deficits, mostly minor, were noted in 15 patients (7.5%) and seizures occurred in 14 patients (7.0%), generally during motor mapping. In three patients (1.5%), the procedure was aborted, and there were two instances of intubation (1%) during a planned awake procedure. One patient (0.5%) experienced mildly elevated ICP, and one patient (0.5%) experienced vascular injury to the middle cerebral artery. Three patients (1.5%) had hemodynamic instability requiring fluid boluses and rapid titration of vasopressors. In one patient (0.5%), it was necessary to perform a craniectomy due to severe cerebral edema.

Eighteen patients experienced early postoperative complications in the PACU or received emergent imaging. The most frequent complications were new focal neurologic deficit in eight patients (4.0%). Five patients were unable to be extubated due to delayed emergence from anesthesia or persistently altered mental status. Five patients received an unplanned, emergent head CT. One patient (0.5%) experienced a seizure. No patients were reintubated, returned to the OR, or experienced an ischemic stroke or symptomatic intracerebral hemorrhage while in the PACU. There were also no episodes of hypotension requiring intervention, hypertension requiring IV infusion, severe respiratory insufficiency, or significant arrhythmia.

ICU Complications

Nineteen patients (9.5%) experienced complications or underwent unplanned emergent imaging while in the ICU (**Supplemental Fig. 1**, Supplemental Digital Content 1, http://links.lww.com/CCM/D596; **legend**, Supplemental Digital Content 3, http://links.lww.com/CCM/D598). Seizures occurred in six patients (3%). Two patients (1%) experienced symptomatic hematoma. It was necessary for two patients (1%) to return to the OR for hematoma evacuations. New unexpected focal neurologic deficits also occurred in three (1.5%). Areas of restricted diffusion suggestive of ischemia were detected on postoperative MRI in four (2%), and one patient (0.5%) experienced a venous infarction. Two (1%) experienced acute respiratory failure, and one (0.5%) required reintubation. Seven patients (3.5%) received an emergent, unplanned CT scan. No patients experienced tension pneumocephalus, acute coronary syndrome, shock, required vasopressors, or experienced significant cardiac arrhythmias.

TABLE 1. Demographic and Clinical Information for 200 Patients in the Derivation Cohort

Patient Characteristics	Mean (SD) or *n* (%)
Age, mean (SD)	53.6 (14.7)
Female, *n* (%)	87 (43.5)
Charlson Index, mean (SD)	3.9 (5.8)
Body mass index, mean (SD)	28.9 (6.5)
Preoperative Glasgow Coma Scale, mean (SD)	14.9 (0.7)
Admitted from home, *n* (%)	177 (88.5)
Karnofsky Performance Status scale score < 70, *n* (%)	39 (19.5)
Awake craniotomy, *n* (%)	73 (36.5)
Operative length (hr), mean (SD)	4.7(2.6)
Intraoperative MRI, *n* (%)	48 (24)
Tumor type, *n* (%)	
Glioblastoma	58 (29.0)
Metastasis	55 (27.5)
Low-grade glioma	32 (16.0)
Meningioma	26 (13.0)
Anaplastic glioma	17 (8.5)
Other	9 (4.5)
Unknown	2 (1.0)
Lymphoma	1 (0.5)
Postanesthesia care unit LOS (hr), mean (SD)	2.4 (1.2)
ICU admission < 24 hr, *n* (%)	174 (87)
Hospital LOS, mean (SD)	3.5 (2.9)

LOS = length of stay.

Receipt of ICU-Specific interventions

Of 200 patients, 18 patients (9%) received 24 different ICU-specific interventions (Supplemental Fig. 1, Supplemental Digital Content 1, http://links.lww.com/CCM/D596; legend, Supplemental Digital Content 3, http://links.lww.com/CCM/D598). The most common interventions were EVD in seven (3.5%), hypertonic saline to treat cerebral edema in six (3.0%), and mechanical ventilation in six (3.0%). Three patients (1.5%) received an IV antihypertensive infusion, one patient (0.5%) received NIPPV to treat respiratory failure, and one (0.5%) was treated for status epilepticus. No patients were treated with vasopressors. Although most patients received only one ICU-specific intervention, four received two ICU-specific interventions, and one patient received three (EVD, hypertonic saline, and mechanical ventilation).

Univariate and Multivariate Analysis of Factors Associated With ICU-Specific Interventions

Differences in patient characteristics between those who did and did not receive ICU-specific care are shown in **Table 2**. Factors associated with ICU-specific care were nonelective admission (38.9% vs 8.2%; $p = 0.0011$), ICU admission preoperatively (27.8% vs 0.6%, $p < 0.0001$), Karnofsky Performance Status (KPS) less than 70 (55.6% vs 15.9%; $p = 0.0004$), and early postoperative (PACU) complications (66.7% vs 3.3%; $p < 0.001$). Sixteen of 127 patients (12.6%) undergoing general endotracheal anesthesia (GETA) required ICU-specific care; however, only two of 73 patients (2.7%) who underwent awake craniotomy required ICU-specific care. Patients who did not receive ICU-specific care also had a higher preoperative Glasgow Coma Scale (15.0 vs 14.1 $p = 0.0001$), lower ASA (2.7 vs 3.1, $p = 0.01$), and received less IV fluids (2.7 L vs 3.3 L,

TABLE 2. Univariate Analysis Comparing Patients who Received and Did Not Receive ICU-Specific Care in the Derivation Cohort

Characteristics	No ICU-Specific Care	ICU-Specific Care	*p*
Patients, *n* (%)	182 (91)	18 (9)	
Age, mean (SD)	53.5 (14.6)	54.7 (16.0)	0.73
Charlson Index	3.9 (6.1)	3.4 (1.9)	0.57
Female, *n* (%)	83 (45.6)	4 (22.2)	0.06
Nonelective admit, *n* (%)	15 (8.2)	7 (38.9)	0.001
Admit source, *n* (%)			0.002
Home	166 (91.2)	11 (61.1)	
Emergency department	12 (6.6)	6 (33.3)	
Transfer	4 (2.2)	1 (5.6)	
ICU preoperatively, *n* (%)	1 (0.6)	5 (27.8)	< 0.0001
Karnofsky Performance Status scale score < 70, *n* (%)	29 (15.9)	10 (55.6)	0.0004
Preoperative deficit, *n* (%)	71 (39.0)	9 (50.0)	0.36
Glasgow Coma Scale, mean (SD)	15.0 (0.3)	14.1 (1.9)	0.0001
Body mass index, mean (SD)	28.6 (6.1)	31.5 (9.1)	0.13
Awake procedure, *n* (%)	71 (39.0)	2 (11.1)	0.02
American Society of Anesthesiologists classification, mean (SD)	2.7 (0.5)	3.1(0.6)	0.01
Intraoperative MRI, *n* (%)	45 (24.7)	3 (16.7)	0.57
Operative length (hr), mean (SD)	4.7 (2.70)	5.4 (1.77)	0.16
Estimated blood loss (mL), mean (SD)	220 (237)	261 (197)	0.17
IV fluid (L), mean (SD)	2.7 (1.0)	3.3 (1.2)	0.03
Intraoperative complications, *n* (%)	33 (18.1)	5 (27.8)	0.35
Early postoperative (postanesthesia care unit) complications, *n* (%)	6 (3.3)	12 (66.7)	< 0.0001
Tumor type, *n* (%)			0.23
Glioblastoma	52 (28.6)	6 (33.3)	
Anaplastic glioma	17 (9.3)	0	
Lymphoma	1 (0.6)	0	
Low-grade glioma	30 (16.5)	2 (11.1)	
Meningioma	20 (11.0)	6 (33.3)	
Metastasis	52 (28.6)	3 (16.7)	
Unknown	2 (1.1)	0	
Other	8 (4.4)	1 (5.6)	

TABLE 3. Multivariate Logistic Regression Model Predicting ICU-Specific Care

Characteristics	OR	95% CI	p
Karnofsky Performance Status < 70	6.7	1.4–31.4	0.02
General endotracheal anesthesia	8.5	1.2–61.4	0.03
Early postoperative complications	111.7	18.6–670.6	< 0.001

OR = odds ratio.

$p = 0.03$). A simple model (**Table 3**) containing three covariates (KPS < 70, GETA, and early postoperative complications) predicted the need for ICU-specific care with excellent discrimination (C-statistic = 0.92) and was well calibrated (Hosmer-Lemeshow $p = 0.91$).

Prediction Score to Stratify Risk After Supratentorial Brain Tumor Surgery

The covariates in the above model were used to develop a simple prediction scale, the Brain Tumor ICU score, with higher values indicating greater likelihood of requiring ICU-specific care (**Table 4**). The score includes the following components: KPS less than 70 (1 point), GETA (1 point), and early postoperative complications (2 points). In the initial 200-patient dataset from which it was derived, the score showed excellent discrimination (C-statistic = 0.91) and was well calibrated (Hosmer-Lemeshow $p = 0.89$). As shown in **Table 5**, 55 patients (27.5%) in the training set had an ICU score of 0, and none required ICU-specific care. One-hundred four patients (52.0%) had a score of 1, and only three (2.8%) required ICU-specific care. In the remaining categories, 19.2%, 60.0%, and 100.0% of patients required ICU-specific care, respectively. When tested on the validation cohort, the score remained well calibrated (Hosmer-Lemeshow $p = 0.43$) and showed good discrimination (C-statistic = 0.86). The frequency with which patients at all score levels received ICU-specific care in the training, validation, and overall dataset can be seen in **Supplemental Figure 2** (Supplemental Digital Content 2, http://links.lww.com/CCM/D597; legend, Supplemental Digital Content 3, http://links.lww.com/CCM/D598) and Table 5. Of 300 total patients in the combined datasets, 72 (24.0%) had an ICU score of 0, none of whom required ICU-specific care.

TABLE 4. Proposed ICU Score for Predicting Supratentorial Tumor Patients Requiring ICU-Specific Care

Criteria	ICU Score
Karnofsky Performance Status	
≥ 70	0
< 70	1
General endotracheal anesthesia?	
No	0
Yes	1
Early postoperative complications?	
No	0
Yes	2
Maximum score	4

DISCUSSION

Current practice at many institutions is to admit all patients to an ICU after supratentorial tumor resection. However, this sometimes results in delayed patient transfers and cancelled surgeries due to lack of ICU availability and has not been proven to improve outcomes (1, 10). Additionally, caring for less severely ill patients outside of an ICU may result in substantial cost-savings (21). Overall, only 9% of patients required ICU-specific interventions after undergoing a supratentorial tumor removal. The number of patients experiencing new complications or undergoing emergent imaging for any reason was similarly low. The number of major complications was even lower, with only two patients experiencing symptomatic hematoma (1.0%) and two requiring return to the OR (1.0%). These results suggest that it may be possible to safely provide postoperative care for many supratentorial tumor resection patients outside of an ICU, provided that adequate monitoring and timely intervention in the event of a complication can be ensured

Several prior case series have reported outcomes for patients admitted to lower levels of care after neurosurgical procedures (1, 11, 12, 22), and some centers have reported outcomes for same-day discharges (14, 15). These series suggest that admitting selected patients to a lower level of care can be a safe alternative (1, 12). For example, Florman et al (22) reported results of a protocol to admit supratentorial tumor resections patients who were stable 4 four hours of monitoring in the PACU directly to the floor. In their series, 200 of 342 consecutive patients (59%) undergoing elective supratentorial craniotomy for tumor resection bypassed the ICU and were admitted to the floor. Only five patients (2.5%) required transfer to a step-down unit, and none were transferred to the ICU (22).

The protocols for determining the appropriateness of direct admission to the floor or same-day discharge in Florman et al (22) and other similar studies (1, 12, 14, 15) were determined by clinician consensus. In this study, we report objective data on several clinical and operative features that are associated with ICU-specific interventions. Additionally, we describe a simple, internally validated model with excellent ability to discriminate those most likely to require ICU-specific care.

There are relatively few studies that have examined the occurrence rate of ICU-specific interventions and complications in patients undergoing neurosurgical procedures for comparison. Overall, we identified new ICU complications or emergent imaging procedures in 9.5% of patients, which is comparable with that reported in Lonjaret et al (23), where

TABLE 5. Receipt of Critical Care Based on Brain Tumor ICU Score

	Derivation Set		Validation Set		All Patients	
Score	No ICU Care, *n*	ICU Care, *n* (%)	No ICU Care, *n*	ICU Care, *n* (%)	No ICU Care, *n*	ICU Care, *n* (%)
0	55	0 (0.0)	17	0 (0.0)	72	0 (0.0)
1	104	3 (2.8)	59	2 (3.3)	163	5 (3.0)
2	21	5 (19.2)	11	4 (26.7)	32	9 (22.0)
3	2	3 (60.0)	1	2 (66.7)	5	3 (62.5)
4	0	7 (100.0)	2	2 (50.0)	2	9 (81.8)
Totals	182	18 (9.0)	90	10 (10.0)	272	28 (9.3)

16% of patients undergoing craniotomy for tumor resection experienced neurologic complications within the first 24 hours.

In this study, we primarily focused on the delivery of interventions that are limited to ICUs at our institution. Direct comparison of rates of ICU-specific interventions is hampered by differences in institutional protocols and practices with respect to what interventions are considered ICU specific. For example, Ziai et al (24) found that 51% of patients remaining in the ICU for less than 24 hours required ICU-specific interventions after undergoing infratentorial and supratentorial tumor resections. However, interventions such as IV analgesics, which are not limited to an ICU setting at our institution, were counted toward this number. In the study by Hanak et al (5), 35% of patients required ICU-specific interventions or experienced an ICU complication after elective craniotomy. In over 30% of patients, a continuous IV antihypertensive was administered in the ICU, whereas only 1.5% of patients were administered a continuous antihypertensive infusion in our study. This difference likely reflects institutional preferences with regard to blood pressure goals and the use of bolus versus continuous IV antihypertensives in the ICU. Insulin infusions were also considered to be an ICU-level intervention by Hanak et al (5), but at our institution, these are permitted on step-down units and general care wards.

There are several important limitations of the present study that should be considered when interpreting these results. Since the study took place at a single academic center, these results may not generalize to other institutions. In particular, because the ICU-specific interventions at the study hospital may not be the same at other institutions, the external validity of the predictive model is uncertain and should be examined in future studies. This study is also subject to the weaknesses of any retrospective study dependent on information being accurately recorded in the electronic medical record. Ultimately, additional prospective cohort studies or clinical trials, ideally from multiple institutions, are needed to confirm the safety and utility of delivering postoperative care outside of an ICU in patients undergoing brain tumor resection

CONCLUSIONS

Among consecutive patients undergoing supratentorial brain tumor resection at a single academic neurosurgical center, the number of new complications occurring in the ICU and the frequency of receiving ICU-specific interventions were low. Several patient and operative characteristics are associated with a greater likelihood of receiving ICU-specific care. A simple and intuitive predictive model that includes KPS less than 70, GETA, and occurrence of early postoperative complications has excellent ability to discriminate patients who are likely to receive ICU-specific interventions. These results suggest that it may be safe to avoid routine postoperative ICU admission in selected supratentorial brain tumor patients and provide neurosurgeons and intensivists with a model that can be used to identify such patients.

REFERENCES

1. Beauregard CL, Friedman WA. Routine use of postoperative ICU care for elective craniotomy: A cost-benefit analysis. *Surg Neurol* 2003; 60:483–489
2. Berwick DM, Hackbarth AD: Eliminating waste in US health care. *JAMA* 2012; 307:1513–1516
3. Bates DW, Saria S, Ohno-Machado L, et al: Big data in health care: Using analytics to identify and manage high-risk and high-cost patients. *Health Aff (Millwood)* 2014; 33:1123–1131
4. Min D, Yih Y. Scheduling elective surgery under uncertainty and downstream capacity constraints. *Eur J Op Res* 2010; 206:642–652
5. Hanak BW, Walcott BP, Nahed BV, et al: Postoperative intensive care unit requirements after elective craniotomy. *World Neurosurg* 2014; 81:165–172
6. Kelly DF: Neurosurgical postoperative care. *Neurosurg Clin N Am* 1994; 5:789–810
7. Teplick R, Caldera DL, Gilbert JP, et al: Benefit of elective intensive care admission after certain operations. *Anesth Analg* 1983; 62:572–577
8. de Almeida CC, Boone MD, Laviv Y, et al: The utility of routine intensive care admissions for patients undergoing intracranial neurosurgical procedures: A systematic review. *Neurocrit Care* 2017; 28:35–42
9. Rhondali O, Genty C, Halle C, et al: Do patients still require admission to an intensive care unit after elective craniotomy for brain surgery? *J Neurosurg Anesthesiol* 2011; 23:118–123
10. Terada Y, Inoue S, Tanaka Y, et al: The impact of postoperative intensive care on outcomes in elective neurosurgical patients in good physical condition: A single centre propensity case-matched study. *Can J Anaesth* 2010; 57:1089–1094
11. Richards BF, Fleming JB, Shannon CN, et al: Safety and cost effectiveness of step-down unit admission following elective neurointerventional procedures. *J Neurointerv Surg* 2012; 4:390–392
12. Bui JQ, Mendis RL, van Gelder JM, et al: Is postoperative intensive care unit admission a prerequisite for elective craniotomy? *J Neurosurg* 2011; 115:1236–1241

13. Stetler WR Jr, Griauzde J, Saadeh Y, et al: Is intensive care monitoring necessary after coil embolization of unruptured intracranial aneurysms? *J Neurointerv Surg* 2017; 9:756–760
14. Venkatraghavan L, Bharadwaj S, Au K, et al: Same-day discharge after craniotomy for supratentorial tumour surgery: A retrospective observational single-centre study. *Can J Anaesth* 2016; 63:1245–1257
15. Boulton M, Bernstein M: Outpatient brain tumor surgery: Innovation in surgical neurooncology. *J Neurosurg* 2008; 108:649–654
16. Grundy PL, Weidmann C, Bernstein M: Day-case neurosurgery for brain tumours: The early United Kingdom experience. *Br J Neurosurg* 2008; 22:360–367
17. Dubey A, Sung WS, Shaya M, et al: Complications of posterior cranial fossa surgery–an institutional experience of 500 patients. *Surg Neurol* 2009; 72:369–375
18. Mohammed-Ali RI, Robbins AE, Hussain O, et al: Six-year retrospective study of reconstructive options for defects of the skull base after resection of tumour. *Br J Oral Maxillofac Surg* 2013; 51:719–724
19. Komotar RJ, Starke RM, Raper DM, et al: Endoscopic endonasal versus open transcranial resection of anterior midline skull base meningiomas. *World Neurosurg* 2012; 77:713–724
20. Harris PA, Taylor R, Thielke R, et al: Research electronic data capture (REDCap)–a metadata-driven methodology and workflow process for providing translational research informatics support. *J Biomed Inform* 2009; 42:377–381
21. Norris C, Jacobs P, Rapoport J, et al: ICU and non-ICU cost per day. *Can J Anaesth* 1995; 42:192–196
22. Florman JE, Cushing D, Keller LA, et al. A protocol for postoperative admission of elective craniotomy patients to a non-ICU or step-down setting. *J Neurosurg* 2017; 127:1392–1397
23. Lonjaret L, Guyonnet M, Berard E, et al: Postoperative complications after craniotomy for brain tumor surgery. *Anaesth Crit Care Pain Med* 2017; 36:213–218
24. Ziai WC, Varelas PN, Zeger SL, et al: Neurologic intensive care resource use after brain tumor surgery: An analysis of indications and alternative strategies. *Crit Care Med* 2003; 31:2782–2787