Complications of invasive intracranial pressure monitoring devices in neurocritical care

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Intracranial pressure monitoring devices have become the standard of care for the management of patients with pathologies associated with intracranial hypertension. Given the importance of invasive intracranial monitoring devices in the modern neurointensive care setting, gaining a thorough understanding of the potential complications related to device placement—and misplacement—is crucial. The increased prevalence of intracranial pressure monitoring as a management tool for neurosurgical patients has led to the publication of a plethora of papers regarding their indications and complications. The authors aim to provide a concise review of key contemporary articles in the literature concerning important complications with the hope of elucidating practices that improve outcomes for neurocritically ill patients.

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INTRACRANIAL pressure (ICP) monitoring and external CSF drainage are fundamental to the management of neurosurgical patients in the critical care setting, and current methods have evolved considerably since the early days of neurosurgery. The first documented ventricular cannulation and drainage was performed in 1744 when Claude-Nicolas Le Cat treated a child with congenital hydrocephalus by draining ventricular CSF via a specially designed wick for 5 days, until the patient died (Fig. 1).⁵⁴ During the 18th and 19th centuries, the techniques and materials for ventriculostomy improved, and the indications expanded. In 1898, Fedor Krause described the use of ventricular drainage perioperatively in posterior fossa surgery,⁵² and in 1918, Walter Dandy described ventriculography after injecting air into the ventricles.¹² By the early 20th century, manometry was incorporated, allowing ICP measurement. External ventricular drains (EVDs) were being used for continuous ICP monitoring in patients with brain tumors by the 1960s and for patients with subarachnoid hemorrhage (SAH) and patients with traumatic brain injury (TBI) by the 1980s.⁵⁴ Currently, the Brain Trauma Foundation 4th edition guidelines provide a Level IIB recommendation for the use of ICP monitoring in the management of patients with severe TBI to reduce in-hospital and 2-week postinjury mortality.⁹

Technical difficulties and complications associated

with ventricular catheterization led to the development of fiberoptic and miniature strain-gauge sensors that could be placed in the subdural space, parenchyma, or ventricle for ICP monitoring. The reliability and efficacy of such devices were studied during the 1990s and found to be reasonably accurate compared with EVDs.^{23,24,26} Although EVDs remain the gold standard in ICP monitoring due to their ability to be zeroed in vivo as well as their ability to drain CSF, intraparenchymal and subdural monitors are preferred in some cases or by some providers because of the latter's comparative ease of placement and perceived lower risk of complications. Herein, the types and frequencies of complications for EVDs and ICP monitors (ICPMs) are discussed.

Complications of EVDs and ICPMs

Infection Rates

Ventriculostomy-associated infections (VAIs), or ventriculostomy-related infections, are the most common complication associated with placement of EVDs; the rate of VAIs was estimated in one meta-analysis to be 0%–22%, with an average rate of 8.8% (Table 1).^{39,42,48} In a recent retrospective study of 288 patients comparing complication rates in EVDs and ICPMs, Dimitriou et al. found rates of infection to be 9.2% and 0.8%, respectively. In ad-

ABBREVIATIONS AI = antibiotic impregnated; DVT = deep venous thrombosis; EVD = external ventricular drain; ICP = intracranial pressure; ICPM = ICP monitor; ICU = intensive care unit; OR = operating room; SAH = subarachnoid hemorrhage; TBI = traumatic brain injury; VAI = ventriculostomy-associated infection; VTE = venous thromboembolism.

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FIG. 1. Portrait of Claude-Nicolas Le Cat (1700–1768), French surgeon who performed the first recorded ventriculostomy for drainage of CSF. Public domain.

dition, they found that infection rates were increased in the presence of SAH (9.4%), intraventricular hemorrhage (8.6%), and concomitant catheters (3.5%), with the greatest incidence occurring between the 5th and 11th day after placement.¹⁶

With regard to ICPMs, Guyot et al. reported no infections in 229 patients who underwent placement of Camino (Integra LifeSciences) intraparenchymal ICP monitors;²⁷ in addition, rates of infection with concurrent placement of EVDs and ICPMs seem to be similar to those of EVD placement alone.^{2,5} To date, the majority of studies reporting VAI rates have been in TBI-predominant patient populations; however, in a large retrospective analysis of 116,813 patients with aneurysmal SAH, 32.9% were managed with EVDs, with a mean annual rate of infection of 7.3%.⁴⁸

In a similar retrospective analysis of the Nationwide Inpatient Sample of 34,238 patients with spontaneous intracranial hemorrhage, a subset of patients with VAIs had an overall significant increase in the rate of inpatient

mortality, length of stay, and cost of care. Predictors of VAI in their analysis included increased age, male sex, presence of medical comorbidities or systemic infections, and longer hospital length of stay.⁴⁴ VAI is an important controllable risk factor that can significantly affect patient outcomes.

Although infection is the most common complication associated with invasive intracranial monitor placement, there is no consensus-accepted standard definition for VAI, which limits the study, surveillance, and comparison of practices. In a literature search performed by Lewis et al., 16 different definitions for VAI were found, 9 of which were subjective. After applying definitions to a test cohort, they found that the frequency of infection ranged from 22% to 94%.³⁸ To further illustrate the variability in defining VAIs, one study applied criteria from Honda et al., Gozal et al., and Citerio et al. to a retrospective series and found that rates of infection based on each authors' criteria were 60%, 56%, and 23%, respectively.^{11,25,30,51}

In 2014, Gozal et al. proposed a standardized definition of VAIs as a positive CSF culture in a patient with a ventriculostomy catheter and one of the following: a fever > 101.5°F, a CSF glucose level < 50 mg/dl, or a CSF glucose level < 50% of any serum glucose drawn within 24 hours of CSF sample.²⁵ Most recently, the 2017 Infectious Diseases Society of America guidelines on health-care-associated ventriculitis and meningitis did not give a definition of VAI, but provided guidance for when clinical suspicion prompts CSF sampling for infection. CSF pleocytosis with a positive culture and infectious symptoms are indicative of VAI, a strong recommendation with a high level of evidence. CSF cultures that grow *Staphylococcus aureus*, aerobic gram-negative bacilli, and fungal pathogens are likely to represent true infection, whereas minimal growth of coagulase-negative *Staphylococcus* in the setting of normal CSF and lack of a fever are probably indicative of a contaminant. Furthermore, there is low-quality evidence for hypoglycorrhachia with elevated CSF protein representing infection.⁵⁸

In a 2017 survey of AANS members regarding EVD infection rates, respondents reported infection rates ranging from 1% to 3%, and 42.7% reported the use of institutional protocols, although almost 33% admitted incomplete adherence to protocols.⁴ This survey highlights that attitudes and perceptions of catheter-related infection are grossly underestimated by individual clinicians and that there exists significant heterogeneity in practice and a lack of compliance with institutional protocols.

There is insufficient evidence regarding the risks and benefits of prophylactic antibiotic administration with invasive intracranial monitoring. Multiple retrospective studies comparing the administration of prophylactic antibiotics periprocedurally or for the duration of monitoring have not been able to demonstrate a decreased risk of VAIs compared with patients who did not receive antibiotics.^{32,50,55} In fact, Jacobs and Westerband found higher rates of sepsis and pneumonia and Stoikes et al. found a higher incidence of multidrug-resistant pathogens in ventilator-associated pneumonia and bloodstream infections in patients to whom antibiotics were administered prophylactically.^{32,50,55} Another randomized trial, which compared

TABLE 1. VAI rates

Authors & Year	Study Design	No. of Cases	Pathology, No. of Cases	Infection Rate	Comments
Dimitriou et al., 2016	Retrospective	288	TBI, 180; vascular, 108	EVD 9.2%; ICPM 0.8%	
Guyot et al., 1998	Retrospective	536	Undifferentiated	EVD 7.3%; ICPM 0.0%; other devices 0.0%	
Park et al., 2004	Retrospective	595	TBI, 75; vascular, 397; tumor, 102; other, 21	EVD 8.6%	VAI rate increased until Day 4
Holloway et al., 1996	Retrospective	584	TBI	EVD 10.4%	VAI rate increased until Day 10
Mayhall et al., 1984	Prospective	172	Undifferentiated	EVD 8.9%	VAI rates at Days 8, 10, & 11 were 21%, 37%, & 42%, respectively
Lozier et al., 2002	Meta-analysis	5733	Undifferentiated	EVD 8.8%	VAI rate 0%–22%
Poblete et al., 2017	Multicenter retrospective	38,431	Aneurysmal SAH	Annual VAI rate 7.3%	

prophylactic trimethoprim-sulfamethoxazole for the duration of monitoring with placebo in patients undergoing ventriculostomy, found no significant difference in VAI rates.⁸ Thus, there is limited evidence for the use of peri-procedural antibiotics for VAI prophylaxis and, perhaps more worrisome, an increased risk of developing multi-drug-resistant pathogens and double the rate of systemic infectious complications (0.7% vs 1.4% per patient).⁵⁰

The use of systemic antibiotics for the duration of monitoring may be more harmful than helpful; however, the use of antibiotic-impregnated (AI) catheters seems to be beneficial (Table 2). Zabramski et al. randomly assigned patients to receive an AI-EVD (n = 149) or standard silicon catheters (n = 139) and found a 7-fold reduction in VAIs as defined by positive CSF culture in patients in whom AI catheters were used compared with the standard catheter group (1.3% vs 9.4%; p = 0.002). In addition, they demonstrated that AI-EVDs were half as likely to become colonized with pathogens (17.9% vs 36.7%; p = 0.0012).⁵⁹

Conversely, in another large, prospective randomized trial comparing 176 patients with AI-EVDs with 181 patients with standard ventricular catheters, there was no significant difference in the rate of VAIs or number of patients treated for suspected VAI.⁴⁹ Furthermore, Harrop et al. described a prospective cohort study in which the introduction of AI-EVDs decreased the VAI rate from 8.2% to 1%.²⁸ Interestingly, the VAI rate increased to 7.6% when the institution reverted to standard catheters due to technical problems with the AI-EVDs; however, when the AI-EVDs were reintroduced, the VAI rate decreased to 0.9%.²⁸

Based on the available evidence and selected studies above, there seems to be a trend toward decreased rates of VAI with AI-EVDs. To this end, the 2016 Neurocritical Care Society consensus statement on neuromonitoring recommended the use of AI-EVDs, and the Brain Trauma Foundation 4th edition guidelines provided a Level III recommendation for the use of AI-EVDs to prevent VAIs.^{9,19}

TABLE 2. VAI rates with antibiotic prophylaxis or AI-EVDs

Authors & Year	Study Design	No. of Cases	Pathology, No. of Cases	VAI Rate	Comments
Jacobs & West-erband, 1998	Retrospective	30	TBI	0% in both cohorts	Increased rates of sepsis (78.6% vs 31.3%) & pneumonia (57.1% vs 18.8%)
Rebuck et al., 2000	Retrospective	215	Intracranial hemorrhage, 95; TBI, 58; aneurysmal SAH, 25; other, 37	7.4% overall	62.5% of patients w/ VAI received prophylactic antibiotics; increased risk w/ EVD, CSF leak, non-CNS infection, duration >5 days, >1 ICPM
Stoikes et al., 2008	Retrospective	155	TBI	0% w/out antibiotic prophylaxis vs 2.4% w/ antibiotic prophylaxis	Rates of infectious complications (0.7% vs 1.4%) & infections secondary to multidrug-resistant pathogens (0.03 vs 0.33 per patient) were greater in patients receiving prophylactic antibiotics
Blomstedt, 1985	Randomized	122	Tumor, 53; low-pressure hydrocephalus, 29; vascular, 18; other, 22	3.7% w/out antibiotic prophylaxis vs 4% w/ antibiotic prophylaxis	
Harrop et al., 2010	Prospective	1961		1% w/ AI-EVD (catheter A) vs 8.2% w/out AI-EVD	0.9% w/ AI-EVD (catheter B) vs 7.6% w/out AI-EVD
Pople et al., 2012	Randomized	357		2.3% w/ AI-EVD vs 2.8% w/ standard catheter	Duration of time to infection (8.8 ± 6.1 vs 4.6 ± 4.2 days) in AI-EVD vs standard catheter
Zabramski et al., 2003	Randomized	288		1.3% w/ AI-EVD vs 9.4% w/ standard catheter	Rates of EVD colonization were 17.9% vs 36.7% in AI-EVD vs standard catheter, respectively

Specific protocols designed to decrease infection rates for EVDs and ICPMs are being used more frequently in institutions and critical care settings around the world. In a prospective study, Chatzi et al. introduced a protocol that included education of surrounding personnel regarding infection control, meticulous handling of the EVD, minimization of CSF sampling from the EVD, and routine replacement of the catheter on Day 7. After initiation of the protocol, VAI rates dropped from 28% in the preintervention period to 10.5%. Notably, patients who were diagnosed with VAIs had a mean length of stay of 44.4 days compared with 20 days in patients who did not experience a VAI ($p < 0.001$), highlighting the significant benefit from a systems, cost, and resources-based perspective of initiating institution-specific protocols.¹⁰ Similarly, protocols instituted by Dasic et al. included training of staff regarding catheter management, use of antibiotics, hair removal, and placement of head dressings, which led to a $> 50\%$ reduction in VAIs in each study.¹³

The influence of duration of catheterization on VAI rates continues to be a topic of clinical debate. The initial study to examine the attributable risk of duration of external ventricular catheterization to VAI was conducted by Mayhall et al. in 1984; the authors found an increase in VAIs, especially after Day 5, and found rates of VAI as high as 21%, 37%, and 42% by Days 8, 10, and 11, respectively.⁴² However, nearly 20 years later, a retrospective study by Park et al. analyzed 595 patients with prolonged EVD catheterization and found that infection rates rose until Day 4 and then plateaued. Their overall infection rate of 8.6% was similar to rates previously published, suggesting that prolonged catheterization > 4 days may not significantly increase the chance of infection.⁴⁷

Similarly, in a retrospective analysis of 584 patients with severe TBI who underwent EVD placement, VAI rates steadily increased until Day 10, after which they plateaued.²⁹ Clinically, the prolonged use of EVDs may be indicated for pathologies such as TBI and aneurysmal SAH, in which cases infection is a more probable complication, likely influenced by the underlying pathology. Although the removal of EVDs as soon as possible is a well-accepted practice, ultimately, therapeutic benefits of the continued use of EVDs should be weighed against the risk of infection.

Postprocedural Hemorrhage

Hemorrhage associated with EVD placement can potentially cause devastating and irreversible injury, with reported incidence rates of 0.7%–41.0% (Fig. 2).^{1,15,21,27,31,34,43,45,50,56} Miller and Tummala described a case series of 482 patients who received an EVD for management of their intracranial hemorrhage; 21.6% of patients had a postprocedural hemorrhage present on images obtained after ventriculostomy. The average volume of the tract hemorrhage was $1.96 \pm 6.48 \text{ cm}^3$, and 2 patients had hemorrhages that required intervention. In this series, decreased platelet levels on admission and an increasing number of EVD placement attempts correlated with an increased risk of hemorrhage.⁴³

Similarly, Gardner et al. found that 41% of 188 EVDs placed resulted in evidence of hemorrhage on postplace-

FIG. 2. Noncontrast head CT oblique sagittal section showing ventriculostomy tract hemorrhage, intraventricular hemorrhage, and ventricular enlargement after removal of an EVD from a patient with a severe TBI. The CT scan was prompted by a decline in mental status within several hours of EVD removal. After CT scanning, a new EVD was placed on the contralateral side.

ment CT images, of which 20 patients had hemorrhages $> 15 \text{ ml}$ and 1 patient required evacuation of a subdural hematoma.²¹ In contrast, other analyses have reported post-EVD-placement hemorrhage rates of 1%–8%, with clinically significant or symptomatic hemorrhages occurring in $< 1\%$ of patients.^{1,27,34,47} In a meta-analysis of 16 studies and 2428 ventriculostomies, Bauer et al. found a 7% cumulative hemorrhage rate, with a 0.8% rate of clinically significant hemorrhage.³

Likewise, in another meta-analysis by Binz et al. of 1790 EVD placements, an overall hemorrhage rate of 5.7% was reported, with clinically significant hemorrhage occurring in $< 1\%$ of patients.⁷ The varied rates of hemorrhage observed following ventriculostomy (Table 3) are probably related to different definitions of hemorrhage, duration of surveillance, indication for placement, treatment of coagulopathies, and variable practice patterns.

The literature regarding rates of hemorrhage following ICPM placement is not well characterized. A retrospective study of 288 patients with EVD and/or ICPM placement found hemorrhages in 2 patients after EVD placement and in 1 patient after ICPM placement, with none of the 3 hematomas requiring surgical evacuation.¹⁶ In another retrospective study of 549 patients managed with Codman Microsensor (Codman Neuro, Codman & Shurtleff, Inc.) ICPMs, 27 patients were found to have a hematoma, 26 of which were $< 1 \text{ cm}^3$, with 1 that was 8 cm^3 .³⁵ Gelabert-González et al. have published the largest retrospective series to date of 1000 patients with ICPMs. Interestingly, in their study, of 87 patients with at least 1 abnormal coagulation parameter, 7 had a catheter-related hemorrhage (8%) compared with 18 hemorrhages among the 903 patients (2%) with normal coagulation parameters.²² This relatively higher risk of hemorrhage in patients with ab-

TABLE 3. Incidence of ventriculostomy-related hemorrhages

Authors & Year	Type of Study	No. of Cases	Hemorrhage Rate	Comments
Guyot et al., 1998	Retrospective	536	EVD hemorrhage rate 3.3%, Camino ICPM hemorrhage rate 0.9%, other devices 0%	
Maniker et al., 2006	Retrospective	160	Hemorrhage rate 32.5%, symptomatic in 2.5%	Majority <4 cm
Sussman et al., 2014	Retrospective	69	Hemorrhage rate 31.9%, symptomatic in 1.4%	Average vol $0.66 \pm 1.06 \text{ cm}^3$
Gardner et al., 2009	Retrospective	188	Hemorrhage rate in ICU 44.3%, hemorrhage rate in OR 34.8%	Trace 51.9%, >15 ml in 10.6%
Dimitriou et al., 2016	Retrospective	288	EVD hemorrhage rate 1.1%, ICPM hemorrhage rate <1%	
Miller & Tummala, 2017	Retrospective	482	Postplacement hemorrhage rate 21.6%, postremoval hemorrhage rate 22.5%	Mean vol $1.96 \pm 6.48 \text{ cm}^3$, mean vol $8.25 \pm 20.34 \text{ cm}^3$
Koskinen et al., 2013	Retrospective	549	Codman microsensor hemorrhage rate 0.04%	96% were <1 cm ³
Gelabert-González et al., 2006	Retrospective	1000	Camino fiberoptic hemorrhage rate 0.025%	w/ ≥ 1 abnormal coagulation parameter 8%, w/ normal coagulation parameters 2%
Bauer et al., 2011	Meta-analysis	2428	Hemorrhage rate 7%, symptomatic in 0.8%	
Binz et al., 2009	Meta-analysis	1790	Hemorrhage rate 5.7%, symptomatic in <1%	
Dey et al., 2015	Systematic review	3079	Hemorrhage rates 0%–41%, symptomatic rates 0%–14.6%	

normal coagulation parameters highlights an important clinical factor to consider when placing ICPMs.

The need for administration of chemical prophylactic agents against venous thromboembolism (VTE) after EVD placement presents a challenge in the management of neurocritically ill patients, for whom physicians must balance the risk of intracranial hemorrhage with the benefit of preventing a deep venous thrombosis (DVT) or pulmonary embolism. In a retrospective review of 99 patients who received 111 EVDs, there was no significant difference in EVD-associated hemorrhagic events between patients who were administered VTE chemoprophylaxis within 24 hours of admission (early) and those who were administered VTE chemoprophylaxis later than 24 hours after admission (delayed) ($p = 0.731$).⁵⁷ Importantly, starting chemoprophylaxis within 24 hours was not associated with a decrease in the number of DVTs found in patients who were clinically suspected to have DVT.

At our institution, Dengler and colleagues retrospectively studied 155 patients with severe TBI who underwent intracranial monitoring and did not find a significant association between the use of DVT chemoprophylaxis and worsening of traumatic intracranial hemorrhage.¹⁴ In this study, the median time to starting DVT prophylaxis was 3.6 days. As opposed to the previous study in patients with TBI, a retrospective study of 46 patients with aneurysmal SAH showed an increased rate of tract hemorrhage and an increased hematoma volume in patients who received subcutaneous unfractionated heparin within 4 hours of EVD placement compared with those who had received it 4–24 hours after EVD placement.²⁰ In light of this, further clinical trials are needed to determine the appropriate interval for beginning VTE chemoprophylaxis after placement of invasive intracranial monitors.

In patients with aneurysmal disease who present with intraventricular hemorrhage and/or SAH causing acute hydrocephalus, EVD placement is a key component of their

management. Furthermore, during the course of their hospitalization, these patients often require antiplatelet agents or heparinization for treatment of their aneurysmal pathology. Relevantly, in a retrospective analysis of patients who were receiving antiplatelet agents, anticoagulation for DVT prophylaxis, or intraprocedural anticoagulation, Leschke et al. studied hemorrhage rates in patients who were undergoing coil embolization for ruptured cerebral aneurysms who had EVDs placed within 24 hours of admission for acute hydrocephalus. They found a minimal, nonsignificant increase in rates of hemorrhage in patients who were receiving antiplatelet agents, anticoagulation for DVT prophylaxis, or intraprocedural anticoagulation.³⁷ Further characterization of the effects of various antiplatelet and anticoagulant agents on the timing of intracranial catheter placement is needed to help inform practitioners of safe and effective practices.

In turn, as practitioners, we are often faced with patients with invasive intracranial monitoring devices who require therapeutic anticoagulation for the treatment of pulmonary emboli, blunt cerebrovascular injuries, or for the secondary prevention of stroke in patients with significant risk factors (e.g., mechanical valve replacements, cardiac thrombus, and so on). In instances when the risk-to-benefit ratio favors therapeutic anticoagulation, we recommend using intravenous unfractionated heparin without bolus dosing and closely monitoring the patient in a neurological intensive care setting with serial bloodwork, CT imaging, and serial neurological examinations.

Misplacement of EVDs

Optimal placement of EVDs is important to ensure adequate drainage and to obtain accurate measurements of ICP waveforms in neurocritically ill patients. Although ventriculostomy is the most commonly performed neurosurgical procedure, there is no standard technique for placement of the catheters. Misplacement of EVDs with a freehand

FIG. 3. Noncontrast sagittal (left) and axial (right) head CT scans demonstrating anterior misplacement of an EVD, with the tip projecting in the interhemispheric fissure.

technique is a common concern, with reported rates ranging from 8% to 45% depending on intracranial pathology and operator technique, experience, and skill.^{1,17,31,34,46,53}

The initial location for bur hole placement at Kocher's point varies in practice, as was found in 7 studies that aimed to assess accuracy of EVD placement. Instructions for its location in the sagittal axis were described as 10–12 cm posterior to the nasion, 10 cm posterior to the supra-orbital ridge, or 1 cm in front of the coronal suture, with the directions in the coronal axis described as 2–3 cm

from midline or in relation to the midpupillary line.^{1,17,31,34,36,46,53} The most common method for placement involves the location of Kocher's point, with the trajectory dictated by aligning the catheter in intersecting planes passing through the ipsilateral tragus and medial canthus (Fig. 3).

Alternatively, alignment of the catheter can be achieved using Dandy's principle of using a trajectory perpendicular to the skull. Failed attempts to cannulate the ventricle most often occur due to aiming lateral to the ventricle (Fig. 4), which highlights the importance of drilling the bur hole properly such that the trajectory of the catheter is not limited. In situations where the calvarial bone is especially thick, an improper bur hole trajectory can prevent ventricular cannulation entirely. Preparation via examination of underlying anatomy and pathology on imaging can help guide placement and should be routine practice.

Many groups have attempted to evaluate and compare the accuracy of EVD placement using different methods and practices. In 2008, Kakarla et al. proposed a new grading system examining 2 factors: location of the catheter tip, and functional status of the catheter for analyzing the accuracy of EVD placement. Grade 1 indicates optimal placement of the catheter tip in the ipsilateral frontal horn or third ventricle, Grade 2 indicates functional placement in the contralateral frontal horn or lateral ventricle, and Grade 3 indicates suboptimal placement in eloquent tissue despite functional status. After applying their novel grading system retrospectively to a series of 346 patients with EVDs placed freehand at the bedside, Grade 1 placement was achieved in 77% of patients, Grade 2 in 10%, and Grade 3 in 13%. The authors noted that suboptimal placement occurred most frequently in patients with TBI and in those with a midline shift on images.³⁴

In 2015, Foreman and colleagues retrospectively applied the grading system of Kakarla et al. to evaluate 138 patients who underwent EVD placement in the intensive care unit (ICU) versus the operating room (OR) setting and revealed that a higher rates of optimally placed (67.7% vs 55.6%) and suboptimally placed (6.5% vs 2.2%) EVDs occurred with placement in the ICU. As would be expected, place-

FIG. 4. Axial susceptibility-weighted MR image demonstrating several punctuate regions of subcortical injury from errant EVD passes. Reprinted from *Neurocritical Care Management of the Neurosurgical Patient*, William Ares, Ramesh Grandhi, Bradley J. Molyneaux, David Okonkwo: Placement and complications of intracranial monitors and lumbar drains, pp 429–437, 2018, with permission from Elsevier.

TABLE 4. Accuracy and misplacement of EVDs

Authors & Year	Type of Study	No. of Cases	Technique	Comments
Accuracy of placement				
Abdoh et al., 2012	Retrospective	56	Freehand	Angular variation $\pm 5^\circ$ in 50% in coronal plane and in 40% in sagittal plane
Ehtisham et al., 2009	Retrospective	29	Freehand	82.8% placed in ipsilateral anterior horn, foramen of Monroe, or 3rd ventricle
Huyette et al., 2008	Retrospective	98	Freehand	56.1% successfully placed in ipsilateral lateral ventricle or foramen of Monroe
Foreman et al., 2015	Retrospective	138	Freehand	67.7% vs 55.6% successful placement in ICU vs OR, 6.5% vs 2.2% required revision
Saladino et al., 2009	Retrospective	212	Freehand	12.3% misplaced, 2.4% required revision
Kakarla et al., 2008	Retrospective	346	Freehand	77% Grade 1 placements, 10% Grade 2 placements, 13% Grade 3 placements
Use of adjunct methods				
Bergdal et al., 2013	Retrospective	154	Tunneled vs bolt	69.1% vs 49.1% optimal placement in bolt vs tunneled, decreased need for revision
Jensen et al., 2016	Retrospective	272	Tunneled vs bolt	40% vs 6.5% need for revision, tunnel vs bolt, respectively
O'Leary et al., 2000	Prospective	49	Freehand vs Ghajar	Fewer catheters crossed midline w/ Ghajar (4% vs 20.8%), fewer no. of passes (1.1 vs 1.5 passes)
AlAzri et al., 2017	Prospective	54	Freehand vs navigation	Grade 1 placement more frequent (94.7% vs 57.1%), suboptimal placement less frequent (5.3% vs 42.9%), fewer number of passes (1.16 vs 1.63 passes) w/ navigation
Mahan et al., 2013	Prospective	34	Stereotactic image guidance	94.1% Grade 1 placements, 5.9% Grade 2 placements
Krötz et al., 2004	Prospective	52	CT guided	100% placement; decreased times to placement & to transfer to ICU

ment in the ICU was most commonly performed for head trauma, whereas OR placements occurred for less emergent cases or when placement occurred in conjunction with other neurosurgical procedures (i.e., aneurysm clipping).¹⁸

Concerns about suboptimal placement of EVDs have led practitioners to develop adjunct methods aimed at improving accuracy. Several centers use a custom-made metal bolt for placement of the catheter to reduce the chance of dislodgment or displacement, especially in patients who are confused and/or combative. For example, Bergdal et al. compared the accuracy of tunneled versus bolt-connected placement of EVDs in a retrospective series of 147 patients who required 154 EVDs. The authors concluded that the use of a bolt system significantly improved accuracy ($p = 0.023$) and decreased the need for catheter revision ($p = 0.006$).⁶

Similarly, Jensen et al. found that complications requiring reinsertion were more frequent in patients with tunneled EVDs compared with a cohort of patients with bolt-connected EVDs (40% vs 6.5%; $p < 0.001$).³³ The Ghajar Guide is a rigid tripod that allows for physical guidance of the catheter at an orthogonal trajectory. In a randomized, prospective study in 49 patients by O'Leary et al., which compared the efficacy of EVD placement using the Ghajar Guide versus conventional placement, use of the Ghajar Guide decreased the number of catheters that crossed the midline (1 vs 5 catheters) and required fewer passes for successful ventricular cannulation (1.1 ± 0.3 vs 1.5 ± 0.9 passes; $p = 0.07$).⁴⁶

The use of adjunctive image guidance is more commonly being used for placement of EVDs. A prospective study that compared EVDs placed with a frameless computer-based neuronavigation guidance system with a ret-

rospective cohort of patients with TBI with EVDs placed freehand found that neuronavigation nearly doubled the likelihood of achieving placement in the ipsilateral lateral ventricle (94.7% vs 57.1%; $p = 0.009$) and required statistically significantly fewer passes (1.16 ± 0.38 vs 1.63 ± 0.86 passes; $p = 0.018$).²

Likewise, Mahan et al. found that stereotactic image-guided placement of EVDs in the ICU setting allowed for near perfect catheter placement; ironically, this occurred at the cost of 40 additional minutes to achieve successful ventricular cannulation compared with historical cohorts.⁴⁰ The increased time that is required to use image guidance may not be the best management option for patients with impending cerebral herniation issues; however, if time allows, an imaging guidance system may improve the likelihood of optimal placement.

In a novel system designed by Krötz et al., CT-guided percutaneous ventriculostomies were performed in 52 prospective patients with a 100% cannulation rate. In their analysis, the authors compared their cohort with a retrospective cohort of patients who received conventional, freehand ventriculostomy placement and found that the procedure time (20 ± 12 vs 45 ± 11 mins) and time to transfer to ICU (69 ± 34 vs 138 ± 34 mins) were significantly decreased ($p < 0.05$). Although there are probably multiple confounding factors affecting the differences in these times, the perfect success rate of this method is attractive for improving patient care.³⁶

Indications for EVD placement are often emergent in nature, and any delay in successful catheterization increases the risks of morbidity and mortality in this patient population. Although various techniques may provide greater accuracy and decrease the need for replacement or

revision of the catheter, they often come with an associated cost—delayed time to placement, which allows for more brain damage to occur before intervention (Table 4). Specifically, placement of EVDs using image guidance, either at the bedside or in the OR, may help increase optimal positioning, but not necessarily functionality, of EVDs. Ultimately, the decision regarding the location and method used for EVD placement should be made on a case-by-case basis and account for the acuity of the patient, the underlying pathology, and known risks.

Conclusions

Invasive intracranial monitoring has changed considerably since its origin in the 18th century, but there are still considerable risks of infection, hemorrhage, and misplacement. The uncertainties regarding an appropriate definition for VAIs, infection prophylaxis, timing of DVT chemoprophylaxis, and ideal method of placement of intracranial monitors highlight the need for further well-designed trials on the subject of limiting complications associated with invasive intracranial monitoring.

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Disclosures

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Author Contributions

Conception and design: all authors. Drafting the article: all authors. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Grandhi.

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