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Perceived Utility of Intracranial Pressure Monitoring in Traumatic Brain Injury: A Seattle International Brain Injury Consensus Conference Consensus-Based Analysis and Recommendations

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BACKGROUND: Intracranial pressure (ICP) monitoring is widely practiced, but the indications are incompletely developed, and guidelines are poorly followed.

OBJECTIVE: To study the monitoring practices of an established expert panel (the clinical working group from the Seattle International Brain Injury Consensus Conference effort) to examine the match between monitoring guidelines and their clinical decision-making and offer guidance for clinicians considering monitor insertion.

METHODS: We polled the 42 Seattle International Brain Injury Consensus Conference panel members' ICP monitoring decisions for virtual patients, using matrices of presenting signs (Glasgow Coma Scale [GCS] total or GCS motor, pupillary examination, and computed tomography diagnosis). Monitor insertion decisions were yes, no, or unsure (traffic light approach). We analyzed their responses for weighting of the presenting signs in decision-making using univariate regression.

RESULTS: Heatmaps constructed from the choices of 41 panel members revealed wider ICP monitor use than predicted by guidelines. Clinical examination (GCS) was by far the most important characteristic and differed from guidelines in being nonlinear. The modified Marshall computed tomography classification was second and pupils third. We constructed a heatmap and listed the main clinical determinants representing 80% ICP monitor insertion consensus for our recommendations.

CONCLUSION: Candidacy for ICP monitoring exceeds published indicators for monitor insertion, suggesting the clinical perception that the value of ICP data is greater than simply detecting and monitoring severe intracranial hypertension. Monitor insertion heatmaps are offered as potential guidance for ICP monitor insertion and to stimulate research into what actually drives monitor insertion in unconstrained, real-world conditions.

KEY WORDS: Algorithms, Consensus development, Intracranial hypertension, Intracranial pressure monitoring, Neurocritical care, Practice guidelines, Traumatic brain injury

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ABBREVIATIONS: ARDS, adult respiratory distress syndrome; BTF, Brain Trauma Foundation; CPP, cerebral perfusion pressure; CWG, consensus working group; DI, diffuse injury; EML, evacuated mass lesions; NEML, nonevacuated mass lesions; P_btO₂, brain tissue oxygen; SIBICC, Seattle International Brain Injury Consensus Conference; sTBI, severe traumatic brain injury; TBI, traumatic brain injury.

Supplemental digital content is available for this article at neurosurgery-online.com.

We performed this exercise by internet using Excel-based matrices (Microsoft Corporation) concatenating admission values for the Glasgow Coma Scale (GCS examination,¹² pupillary status, and the modified Marshall CT Classification scheme¹³). We used the total GCS score (GCSt) or just the motor component (GCSm) for situations where the GCS examination is limited. Patients were posited to be adults, where advanced age (unspecified) was not a determinant factor. Pupillary status reflected size/reactivity and symmetry, with an “unexaminable” option. We reused the Marshall CT Classification modification used for SIBICC I¹¹ and CREVICE,¹⁴ wherein postsurgical CT scans after mass lesion evacuation (EML) were additionally classified by adding the Diffuse Injury Scale (DI I-IV) to the EML label (eg, EML/DI IV). This is intended to increase the sensitivity of postoperative images to those indicators of intracranial hypertension used for nonoperative CTs.

CWG members received Excel-based GCSt and GCSm matrices and indicated their likelihood of monitoring for each combination of the 3 variables. We used a traffic light model, wherein green represented definite placement, red represented no monitoring, and yellow represented uncertainty: Entering G, Y, or R into a cell resulted in the corresponding color being displayed, providing “live” visual feedback.

The response period was from 08 October to 10 December, 2020. Subsequently, we combined responses and displayed the composite monitoring likelihood using a continuous color spectrum from pure green through yellow to pure red.

To demonstrate decision-making coherence, we reproduced heatmaps containing actual voting frequencies within each cell. In addition, we developed heatmaps using only primary green and red labels representing cells meeting ≥80% consensus (the SIBICC threshold^{10,11}). We also developed heatmaps using 50% thresholds, representing simple majority decisions.

We aggregately modeled response tendencies using a fractional logit model, allowing us to model the “unsure” category as exactly halfway between “yes” and “no.” We modeled GCS, Marshall grade, and pupils as categorical fixed effects, as was survey respondent. We used SAS software version 9.4.

Neither IRB/ethics committee approval nor consent was required.

RESULTS

Forty-one CWG participants (98%) completed surveys, producing heatmaps for GCSt and GCSm (Figure 1). Both revealed a preponderance of green, although the frequency of intermediate shades (“greenish”) represents lack of comprehensive consensus for most choices. Red and “reddish” cells (not monitored) were much less common, limited to the highest GCSt/GCSm scores with normal or minimally pathological CTs.

To explore these gradients, we examined the response distribution within individual cells. Figure 2 presents Figure 1 with voting tallies for red, yellow, and green within each cell. Most cells with a strongly yellow cast represent wide variations in voting that included all 3 options—indicating substantial lack of consensus rather than equipose within individuals.

Figure 3 shows which cells represent 80% consensus for or against monitoring (the SIBICC threshold^{10,11}). **Supplemental Figure S1** (<http://links.lww.com/NEU/D796>) shows a threshold of ≥50% (“more probably than not”).

We used logistic regression modeling to characterize factors predicting ICP monitor placement. Regression modeling of the main

effects in models without interactions is presented in Table 1. GCSt or GCSm (depth of coma) was dominant in decision-making. Compared with patients with GCSt 13 to 15, those with GCSt 9 to 12 had approximately 6 times the odds of being monitored, and patients with a GCSt of 6 to 8 were 99 times more likely (95% CI = 74, 132; *P* < .001). Despite current recommendation to monitor patients with GCSt score <9, the actual GCS value below this threshold influenced decision-making in a nonlinear fashion. Contrasted to patients with GCSt 6 to 8, those with a score of 4 to 5 had 34% higher odds of monitor placement, whereas patients with a score of 3 had lower odds (approximately half).

The absence of cisterns (DI III and EML/DI III) and midline shift >5 mm (DI IV and EML/DI IV) predict monitoring at 6 to 17 times greater probability for both the GCS groups. Non-evacuated mass lesions (NEMLS) is associated with monitoring probabilities around three times that of DI I. CT classes of DI II and DI III interact with a history of surgical management (EML); odds are at least 1.9 times higher if that DI class was seen after surgery. Those with DI IV after surgery had slightly lower odds of monitoring than those with DI IV without surgery. Pupillary abnormality increases the odds of monitoring 1.3 to 2.7 times.

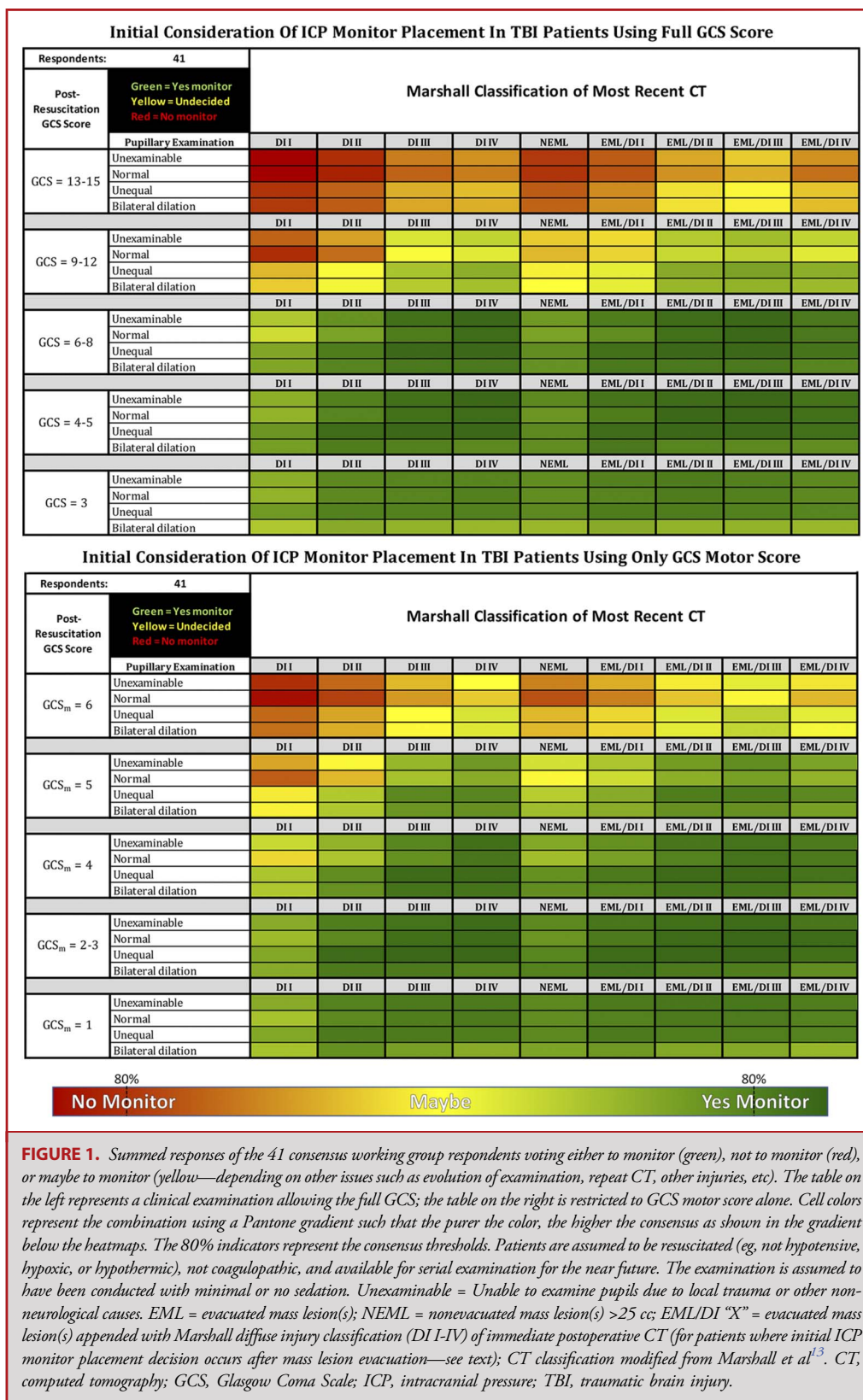
For monitoring, 11 (28%) preferred an external ventricular drain, 9 (23%) preferred an intraparenchymal device (IP), 14 (35%) would choose the device at the time, and 6 (15%) would insert both or a combination monitor.

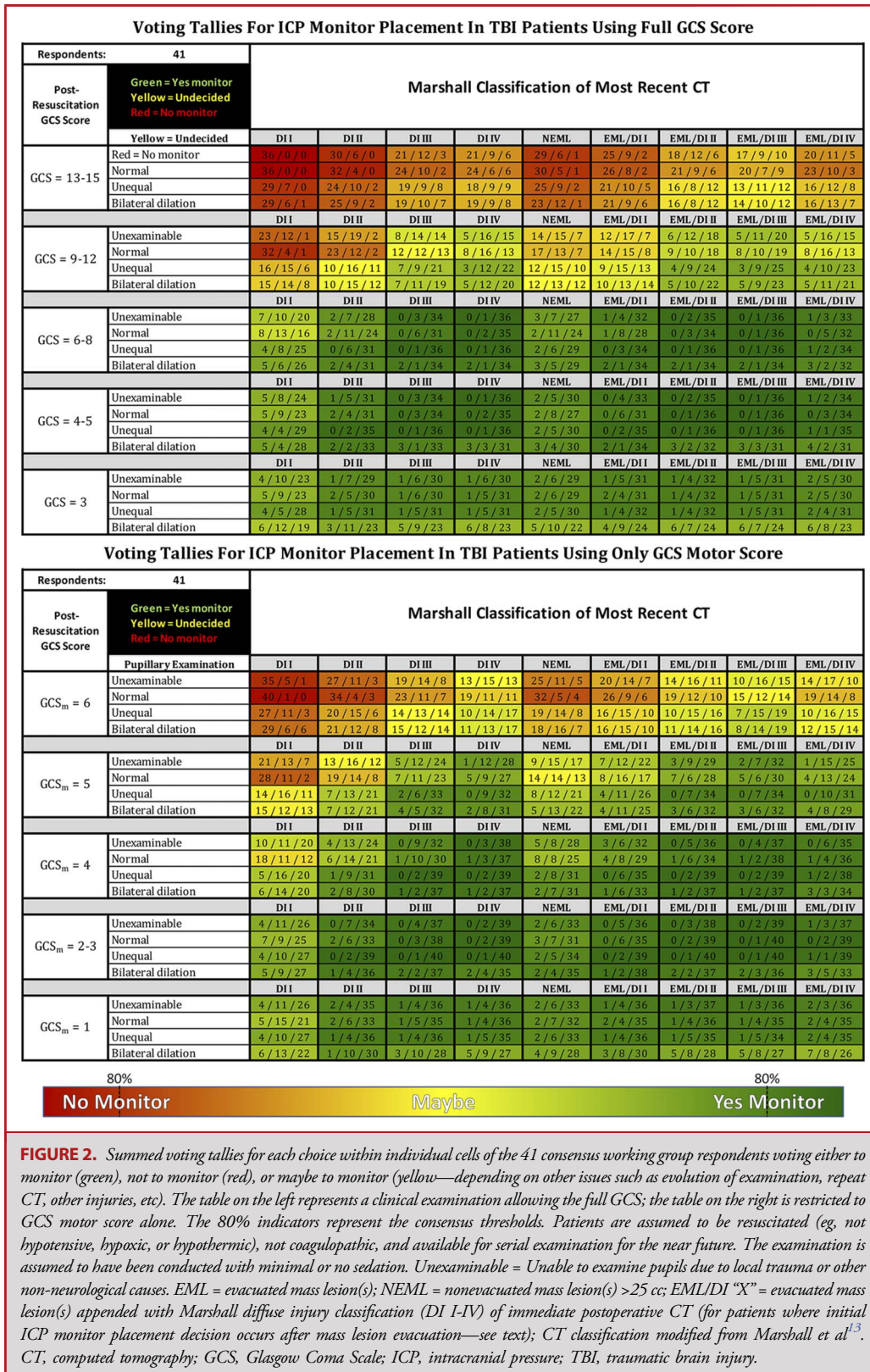
DISCUSSION

Precise ICP monitoring indications are unavailable. Suggested guidelines have low penetrance.^{3,5-7,9} Lacking new evidence, edition 4 of the guidelines² defaulted to edition three’s recommendations¹ based on the incidence of intracranial hypertension in sTBI. They cited Class III papers,¹⁵⁻¹⁹ reporting low incidence of intracranial hypertension with a normal CT to recommend monitoring patients with abnormal imaging. For patients with normal scans, they cited a single retrospective study of 207 patients¹⁸ reporting that the presence of 2 of 3 adverse features (older than 40 years, motor posturing, or systolic BP <90 mm Hg) was associated with an intracranial hypertension incidence similar to patients with abnormal scans.

Studies such as Alali et al²⁰ examine the sensitivity and specificity of models in predicting intracranial hypertension; however, they are limited to the models tested and are not useful in creating new indicators. In addition, no studies have addressed the value of knowing that ICP is normal regarding directing triage and treatment. It often seems that ICP monitoring frequency is as dependent on an institution’s academic focus and resident availability as it is on suspicion of intracranial hypertension.⁴

After the BEST TRIP trial²¹ and its interpretation consensus conference,²² an international group of 14 multidisciplinary TBI experts developed the Milan consensus document on applications of ICP monitoring in TBI.²³ They considered scenarios including diffuse injury, contusions, mass lesion evacuation, and secondary decompressive craniectomy. Consensus was that comatose patients





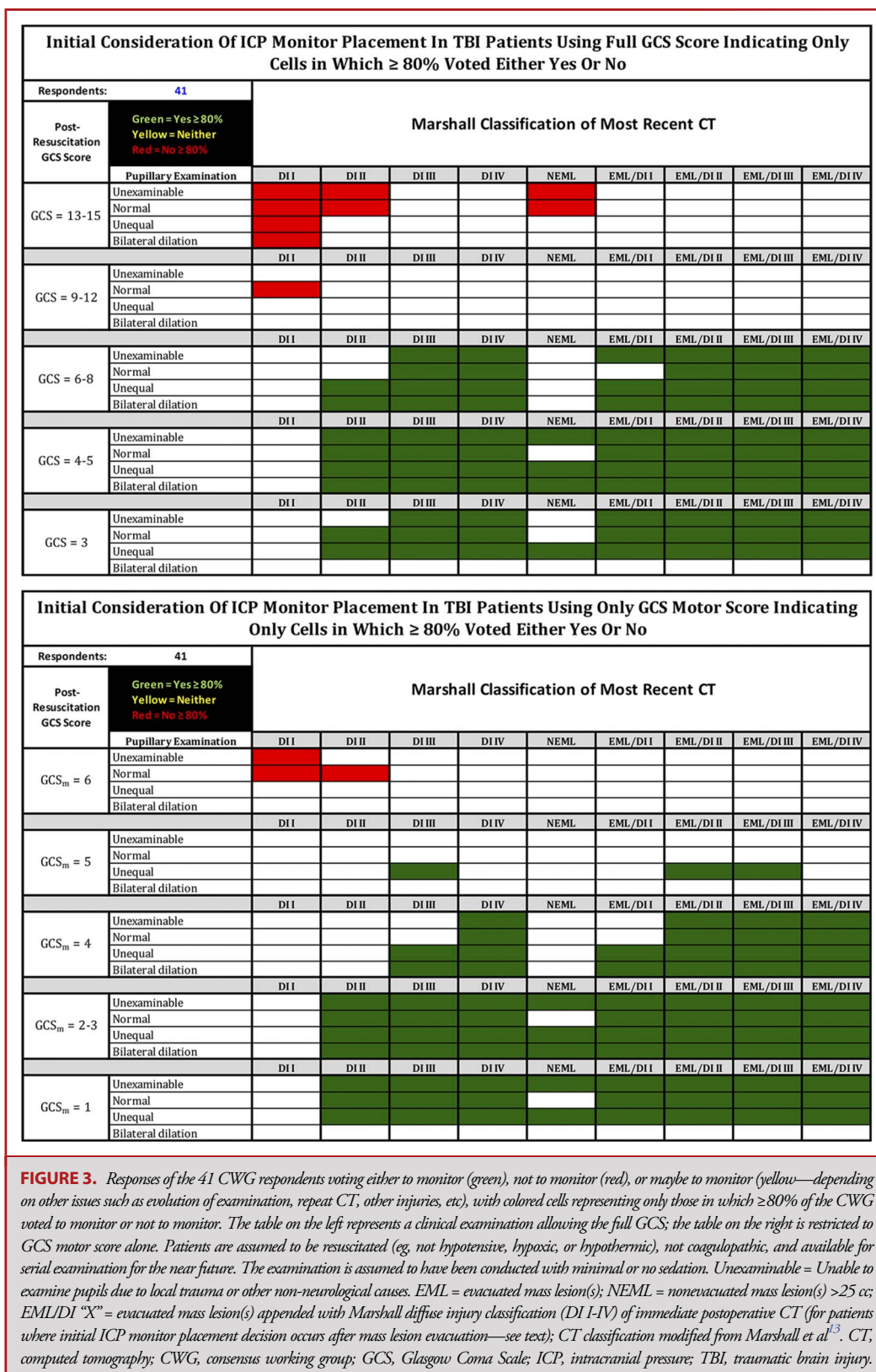


TABLE 1. Regression Modeling of the Association of the 3 Main Variables with ICP Monitor Insertion

Effect	OR	P	Lower	Upper
Regression modeling for GCS_{total} matrix—likelihood of placing an ICP monitor				
Survey ID		<.001		
GCS total		<.001		
9 to 12 (vs 13-15)	5.85	<.001	4.78	7.16
6 to 8 (vs 13-15)	98.79	<.001	74.06	131.78
4 to 5 (vs 13-15)	133.09	<.001	98.06	180.60
3 (vs 13-15)	49.59	<.001	38.41	64.04
Marshall		<.001		
DI II (vs DI I)	2.67	<.001	1.99	3.59
DI III (vs DI I)	6.42	<.001	4.70	8.76
DI IV (vs DI I)	8.02	<.001	5.85	11.01
NEML (vs DI I)	2.43	<.001	1.82	3.26
EML/DI I (vs DI I)	4.40	<.001	3.25	5.95
EML/DI II (vs DI I)	9.99	<.001	7.23	13.79
EML/DI III (vs DI I)	11.74	<.001	8.47	16.29
EML/DI IV (vs DI I)	6.91	<.001	5.05	9.45
Pupils		<.001		
Unexaminable (vs normal)	1.30	.013	1.06	1.60
Unequal (vs normal)	2.27	<.001	1.84	2.81
Bilateral (vs normal)	1.31	.011	1.06	1.61
Regression modeling for GCS_{Motor} matrix—likelihood of placing an ICP monitor				
Survey ID		<.001		
GCS motor		<.001		
5 (vs 6)	7.11	<.001	5.85	8.64
4 (vs 6)	27.89	<.001	22.02	35.33
2 to 3 (vs 6)	63.98	<.001	48.49	84.41
1 (vs 6)	29.17	<.001	22.99	37.00
Marshall		<.001		
DI II (vs DI I)	3.25	<.001	2.49	4.24
DI III (vs DI I)	8.93	<.001	6.67	11.95
DI IV (vs DI I)	13.23	<.001	9.75	17.95
NEML (vs DI I)	3.43	<.001	2.62	4.48
EML/DI I (vs DI I)	6.26	<.001	4.72	8.29

TABLE 1. Continued.

Effect	OR	P	Lower	Upper
EML/DI II (vs DI I)	12.51	<.001	9.24	16.95
EML/DI III (vs DI I)	16.92	<.001	12.34	23.20
EML/DI IV (vs DI I)	9.56	<.001	7.13	12.83
Pupils		<.001		
Unexaminable (vs normal)	1.53	<.001	1.26	1.85
Unequal (vs normal)	2.69	<.001	2.20	3.30
Bilateral (vs normal)	1.74	<.001	1.43	2.11

DI, diffuse injury; EML, evacuated mass lesions; GCS, Glasgow Coma Scale; ICP, intracranial pressure; NEML, nonevacuated mass lesions

DI I, diffuse injury I (“no visible intracranial pathology seen on CT scan”)¹³; DI II, diffuse injury II (“cisterns are present with midline shift of 0 to 5 mm and/or: lesion densities present; no high-density or mixed-density lesion >25 cc; may include bone fragments and foreign bodies”)¹³; DI III, diffuse injury III (“cisterns compressed or absent with midline shift 0 to 5 mm, no high-density or mixed-density lesion >25 cc”)¹³; DI IV, diffuse injury IV (“midline shift >5 mm, no high-density or mixed-density lesion >25 cc”)¹³; EML, evacuated mass lesion (“any lesion surgically evacuated”)¹³; NEML, nonevacuated mass lesion (“high-density or mixed-density lesion >25 cc, not surgically evacuated”)¹³

with a normal CT should not undergo monitoring unless the clinical examination was unreliable or unavailable. They recommended monitoring after secondary decompressive craniectomy or mass lesion evacuation, as both are associated with the risk of ICP elevation. Notably, that meeting’s focus reflected the literature in concentrating on the likelihood of intracranial hypertension as the sole indication for ICP monitoring. This differs from the question asked here, which does not specify why a monitor is placed but only whether the information from monitoring would be considered useful.

Extensive experience balancing such concerns in the setting of having or having not monitored ICP over a long, active practice produces heuristic knowledge on which individual experts base their current monitoring decisions. However, generalizability may be clouded by idiosyncrasies arising from individual biases, technical peculiarities, and situational eccentricities (eg, population demographics and health care policies). Summing the experiences of many such clinicians allows analysis of where they agree/disagree while minimizing the influence of such idiosyncrasies. Our heat-maps should, therefore, be viewed more as indicators of when ICP monitoring is considered valuable than when it is purely indicated for treating intracranial hypertension. Such a process provides a snapshot of clinical practice that may be useful to those who not routinely practicing neurotrauma care.

Analyzing “conventional monitoring indicators,” basic regression modeling without interactions (Table 2), confirms that the consciousness examination (GCSt/GCSm) is strongly most determinant in deciding whether to monitor. This supports obtaining a reliable examination with minimal sedation in a resuscitated patient as early as possible by the physician responsible for monitoring decisions.

TABLE 2. Factors Relevant to the Decision-Making Process in Deciding to Monitor ICP in TBI

<ul style="list-style-type: none"> • The risks of monitor insertion and maintenance
<ul style="list-style-type: none"> • The suspicion that ICP is elevated
<ul style="list-style-type: none"> • The concern that the degree of suspected intracranial hypertension will restrict recovery if not actively managed
<ul style="list-style-type: none"> • The concern for neuroworsening if quantitative ICP is not known
<ul style="list-style-type: none"> • The prognostic value of knowing that intracranial hypertension is extreme/refractory to treatment as a sign of very severe primary disease
<ul style="list-style-type: none"> • The value of quantitative ICP in facilitating evaluation of treatment escalation (eg, tier 3 intervention)
<ul style="list-style-type: none"> • The risks of overtreating ICP (with and without quantitative ICP data)
<ul style="list-style-type: none"> • The value of quantitative ICP in <ul style="list-style-type: none"> ○ Guiding resuscitation (eg, CPP maintenance) ○ Calculating CPP and facilitating CPP-directed therapy ○ Enabling determination of a patient’s autoregulatory status ○ Assisting in the understanding of other cranial monitors (pupillometry, P_{bt}O₂, etc.)
<ul style="list-style-type: none"> • The value of a quantitative monitor in providing an early warning system for potential neuroworsening in a busy or nonspecialist environment
<ul style="list-style-type: none"> • The value of knowing that ICP is NOT elevated <ul style="list-style-type: none"> ○ Allowing other nonurgent systemic surgeries to be performed early ○ Allowing other nonurgent cranial surgeries to be performed early ○ Facilitating treatment of systemic abnormalities (eg, proning for ARDS) ○ Facilitating extubation and transfer from ICU

ARDS, adult respiratory distress syndrome; CPP, cerebral perfusion pressure; ICP, intracranial pressure; ICU, intensive care unit; P_{bt}O₂, brain tissue oxygen; TBI, traumatic brain injury.

Absent or compressed basal cisterns or a midline shift of >5 mm were also strongly associated with monitoring, as was an abnormal pupillary examination (with less magnitude). For patients with GCSt/GCSm scores below the 80% thresholds, imaging and pupil data moderated the monitoring decision. This is demonstrated in the decision to monitor patients with lower GCSt/GCSm scores and a normal (DI I) CT scan or the classification of NEML as well as the decision to not monitor in patients with higher GCSt/GCSm scores. The magnitude of the effects of these variables underlies the “better safe than sorry” theme permeating this study. Apparently, the “time is brain” concept makes monitoring seem preferable to simple observation in marginal cases where waiting for signs of intracranial hypertension might

TABLE 3. Consensus-Based Recommendations for ICP Monitor Insertion Based on 80% Agreement^a

<p>When total GCS score is available:</p> <ul style="list-style-type: none"> • Patients not having undergone cranial surgery should be monitored if: <ul style="list-style-type: none"> ○ GCS score ≤8 with an abnormal CT other than NEML <ul style="list-style-type: none"> ▪ If CT classification is DI II and no pupillary abnormality consensus was <80% ○ The CT classification is NEML and the GCS score is ≤4 with abnormal pupils • Postoperative patients should be monitored if: <ul style="list-style-type: none"> ○ GCS ≤8 ○ If CT classification is DI II and the pupillary examination is normal, consensus was < 80% • Patients do not require ICP monitor insertion if: <ul style="list-style-type: none"> ○ GCS 13 to 15 <ul style="list-style-type: none"> ▪ With a normal CT scan ▪ With a CT classification of DI II or NEML and no pupillary abnormality
<p>When only the GCSm score is reliably available:</p> <ul style="list-style-type: none"> • Patients not having undergone cranial surgery should be monitored if: <ul style="list-style-type: none"> ○ GCSm < 3 with an abnormal CT other than NEML ○ GCSm = 4 with: <ul style="list-style-type: none"> ▪ A CT classification of DI III and abnormal pupils ▪ A CT classification of DI IV ○ The CT classification is NEML and the GCSm score is ≤3 with abnormal pupils • Postoperative patients should be monitored if: <ul style="list-style-type: none"> ▪ GCSm ≤4 unless the CT is normal and there is no pupillary abnormality • Patients do not require ICP monitor insertion if: <ul style="list-style-type: none"> ○ GCSm = 6, the CT is normal and there is no pupillary abnormality ○ GCSm = 6, the CT classification is DI II and the pupils are normal

GCS, Glasgow Coma Scale¹²; GCSm, Glasgow Coma Scale motor component¹²; ICP, intracranial pressure; CT, computed tomographic imaging of the brain; DI I, diffuse injury I (“no visible intracranial pathology seen on CT scan”¹³; DI II, diffuse injury II (“cisterns are present with midline shift of 0 to 5 mm and/or: lesion densities present; no high-density or mixed-density lesion >25 cc; may include bone fragments and foreign bodies”¹³; DI III, diffuse injury III (“cisterns compressed or absent with midline shift 0 to 5 mm, no high-density or mixed-density lesion >25 cc”¹³; DI IV, diffuse injury IV (“midline shift >5 mm, no high-density or mixed-density lesion >25 cc”¹³; EML, evacuated mass lesion (“any lesion surgically evacuated”¹³; NEML, nonevacuated mass lesion (“high-density or mixed-density lesion >25 cc, not surgically evacuated”¹³).

^aAlthough these recommendations meet the 80% consensus threshold, consideration of monitoring in situations outside these thresholds is strongly supported by the results shown in the full heatmaps (Figure 1) and the regression coefficients (Table 1).

produce treatment delay. This is exemplified in the NEML group, which, as a pot-pouri, supports the importance of individualized decision-making.

These data reveal a strong predilection toward monitoring a much wider spectrum of patients with TBI, as represented in the full heatmaps (Figure 1), and emphasized by the regression coefficients (Table 2) and the 50% threshold heatmaps (Figure S1). The monitoring frequencies in “mild or moderate” patients are particularly notable and, certainly, more aggressive than either the guidelines^{1,2} or the Milan consensus statements.²³ This monitoring frequency undoubtedly surpasses the actual incidence of ICP elevation in these patients,^{1-3,23} suggesting that the CWG places value on sensitivity over specificity (not missing intracranial hypertension) in addition to roles for other, nonthreshold decision-making factors, such as those suggested in Table 2. Notably, some of these broader goals might be achieved using less invasive or semiquantitative methods.

Figure 2 presents “yellowish” cells to consist of a mixture of yes, no, and maybe votes—more indicative of controversy than indecision. Voters made definite decisions but in opposite directions. This might partially represent the clinical tendency to make a decision rather than remain undecided. Predominantly yellow cells probably further exemplify situations where factors other than GCS score, pupillary examination, and CT classification would influence decision-making. This also suggests possible utility of noninvasive monitoring.

ICP efficacy investigations compare outcomes between monitored and nonmonitored patients. Outside of the BEST TRIP RCT,²¹ studies have not controlled the initial monitoring decision. Efforts to overcome this include either matching groups using propensity analysis or adjusting for differences using regression statistics. Both methods require defining the variables relevant to such decision-making, which routinely consist of measures associated with a high probability of intracranial hypertension. Our findings suggest that other variables, not entered into such adjustments, are important to the monitoring decision, implying that some of the variability in these efficacy studies might result from nonadjusted differences between study groups and not from the influence of monitoring per se. Our results do not delineate these “occult” variables (eg, Table 2), but they strongly support their existence.

Our second goal was to provide a tool that might be useful in monitor insertion decision-making. The CWG believe that examining the consensus regarding the decision to place an ICP monitor within the group responsible for the SIBICC documents would be useful to nonexpert practitioners who less frequently manage TBI and are faced with such a decision. Consistent with the SIBICC approach, the 80% consensus heatmaps (Figure 3) and their textual summary (Table 3) represent the CWG’s recommendations regarding monitor insertion based on their combined monitoring tendencies. The 50% threshold heatmaps (Figure S1) are included simply to demonstrate most decisions. None of these should be considered insertion rules. They are offered to assist in decision-making where desired and to perhaps spawn clinicians to question

the basis on which they make decisions that vary from the heatmaps (eg Table 2).

Limitations

Our approach is artificial. Many CWG comments addressed the improbability of many combinations (eg, bilateral pupillary abnormalities with GCS 15 and a DI I CT) as well as the artificial lack of myriad other factors present when making such decisions in actual practice. We acknowledge that factors unaddressed here, such as age, history of hypotension or hypoxia, severe extracranial trauma, and unavailability for repeated clinical examination, will influence monitoring decisions. Although it is impossible to weigh all such factors in a single exercise, this would better represent the actual clinical situation and would modify the CWG’s recommendations based solely on GCS, CT diagnosis, and pupils. One example of such apparent in the heatmaps is the lower tendency to monitor patients with GCS 3 and dilated pupils (Figure 1), likely reflecting futility. These limitations are inherent in the model and should be considered by the reader in interpreting the results. Finally, the hypothetical nature of this exercise may not necessarily reflect the panelist’s actual real-world behavior, although this should not detract from the value of the consensus as simple recommendations.

These heatmaps represent an effort toward assisting practitioners with limited TBI experience (although all may find them useful). “They are not a standard of care or even the best treatment approach in a given instance. They are not legally binding or designed as quality assurance tools. They do not represent the approach of any individual CWG member and should never be substituted for thoughtful judgment. There is no weight of evidence here that implies any necessity of changing practice.”¹¹ As a first foray into investigating the collective perceived utility of ICP monitoring in guiding TBI care, they are for information only regarding clinical care and further scientific investigation.

Although exact indications and management details remain ill-defined, ICP monitoring is a cornerstone of TBI treatment. When uncontrollable monitoring constraints are removed, there is obviously a strong desire for ICP data in TBI, encompassing more than the basic goal of correcting intracranial hypertension. Recognizing that desire and minimizing such constraints present important goals for optimizing global TBI management.

CONCLUSION

The perceived utility of ICP monitoring in TBI, as expressed by experienced, international neurotraumatologists, is underrepresented in current monitoring guidelines. Knowing the ICP seems desirable in a broader spectrum of patients with TBI than simply those with intracranial hypertension. We provide consensus-based insertion heatmaps and recommendations for use in clinical decision-making and in analyzing survey-based ICP monitoring efficacy studies.

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Figure S1. Responses of the 41 CWG respondents voting either to monitor (Green), not to monitor (Red), or maybe to monitor (Yellow—depending on other issues such as evolution of exam, repeat CT, other injuries, etc), with colored cells representing only those in which $\geq 50\%$ of the CWG voted to monitor or not to monitor. The table on the left represents a clinical exam allowing the full GCS; the table on the right is restricted to GCS motor score alone. Patients are assumed to be resuscitated (eg, not hypotensive, hypoxic, or hypothermic), not coagulopathic and available for serial examination for the near future. The exam is assumed to have been done with minimal or no sedation. Unexaminable = Unable to examine pupils due to local trauma or other non-neurological causes. EML = evacuated mass lesion(s); NEML = nonevacuated mass lesion(s) >25 cc; EML/DI “X” = evacuated mass lesion(s) appended with Marshall diffuse injury classification (DI I–IV) of immediate postoperative CT (for patients where initial ICP monitor placement occurs following mass lesion evacuation—see text). CT classification modified from Marshall et al¹³