Isolated subdural hematomas in mild traumatic brain injury. Part 2: a preliminary clinical decision support tool for neurosurgical intervention

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OBJECTIVE A paucity of studies have examined neurosurgical interventions in the mild traumatic brain injury (mTBI) population with intracranial hemorrhage (ICH). Furthermore, it is not understood how the dimensions of an ICH relate to the risk of a neurosurgical intervention. These limitations contribute to a lack of treatment guidelines. Isolated subdural hematomas (iSDHs) are the most prevalent ICH in mTBI, carry the highest neurosurgical intervention rate, and account for an overwhelming majority of all neurosurgical interventions. Decision criteria in this population could benefit from understanding the risk of requiring neurosurgical intervention. The aim of this study was to quantify the risk of neurosurgical intervention based on the dimensions of an iSDH in the setting of mTBI.

METHODS This was a 3.5-year, retrospective observational cohort study at a Level I trauma center. All adult (≥ 18 years) trauma patients with mTBI and iSDH were included in the study. Maximum length and thickness (in mm) of acute SDHs, the presence of acute-on-chronic (AOC) SDH, mass effect, and other hemorrhage-related variables were double-data entered; discrepant results were adjudicated after a maximum of 4 reviews. Patients with coagulopathy, skull fractures, no acute hemorrhage, a non-SDH ICH, or who did not undergo imaging on admission were excluded. Tentorial SDHs were not measured. The primary outcome was neurosurgical intervention (craniotomy, burr holes, intracranial pressure monitor placement, shunt, ventriculostomy, or SDH evacuation). Multivariate stepwise logistic regression was used to identify significant covariates, to assess interactions, and to create the scoring system.

RESULTS There were a total of 176 patients included in our study: 28 patients did and 148 did not receive a neurosurgical intervention. There were no significant differences between neurosurgical intervention groups in 11 demographic and 22 comorbid variables. Patients with neurosurgical intervention had significantly longer and thicker SDHs than nonsurgical controls. Logistic regression identified thickness and AOC hemorrhage as being the most important variables in predicting neurosurgical intervention; SDH length was not. Risk of neurosurgical intervention was calculated based on the SDH thickness and presence of an AOC hemorrhage from a multivariable logistic regression model (area under the receiver operating characteristic curve 0.94, 95% CI 0.90–0.97; $p < 0.001$). With a decision point of 2.35% risk, we predicted neurosurgical intervention with 100% sensitivity, 100% negative predictive value, and 53% specificity.

CONCLUSIONS This is the first study to quantify the risk of neurosurgical intervention based on hemorrhage characteristics in patients with mTBI and iSDH. Once validated in a second population, these data can be used to inform the necessity of interhospital transfers and neurosurgical consultations.

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KEYWORDS mild; traumatic brain injury; neurosurgical intervention; subdural hematoma; predictive modeling

ABBREVIATIONS AIS = Abbreviated Injury Scale; AOC = acute-on-chronic; AUROC = area under the receiver operating characteristic; CCHR = Canadian CT Head Rule; ED = emergency department; GCS = Glasgow Coma Scale; ICH = intracranial hemorrhage; iSDH = isolated subdural hematoma; ISS = Injury Severity Score; IVH = intraventricular hemorrhage; mTBI = mild traumatic brain injury; NOC = New Orleans Criteria for Positive Head CT Scan; NPV = negative predictive value; PPV = positive predictive value.

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MILD traumatic brain injury (mTBI) is the most prevalent TBI severity type.^{3,16} Within the mTBI population, one of the most common types of intracranial hemorrhages (ICHs) is an isolated subdural hematoma (iSDH).^{17,18,32} In a study examining 12 years' worth of hospital records obtained in patients with mTBI and ICH across two states, iSDHs accounted for nearly 80% of all neurosurgical interventions, and had the highest neurosurgical intervention rate (16%) among all ICH types.¹⁸ Because an estimated 84% of these patients will not require a neurosurgical intervention, but are treated as though they might, they consume hospital resources, including potentially unnecessary transfer from facilities without neurosurgical capabilities to those with neurosurgical capabilities, and could benefit from accurate prediction models for the likelihood of a need for neurosurgical intervention.

The creation of a decision support tool for patients with mild iSDHs would be beneficial for several reasons. Decision support tools and associated data could inform the formation of more detailed management algorithms whose distal decision pathways would be guided by a patient's probability of a neurosurgical intervention.⁵ Additionally, decision support tools could increase efficiency of hospital resource utilization. Currently, the American College of Surgeons recommends a neurosurgical consultation for any trauma patient with abnormalities on head CT.¹ Requesting neurosurgical consultations for all patients increases health care costs for the patient and the system, especially when patients present to facilities without neurosurgical coverage, and consumes vital neurosurgical resources. However, if neurosurgical consultations were only requested when the risk for a neurosurgical intervention reached a specified threshold, then resource utilization and efficiency of the system could improve, while maintaining patient safety. To date, there has been minimal research devoted to identifying accurate predictors of neurosurgical intervention in this population, and as such, recommendations do not incorporate these decision criteria.

Two scoring systems, the Canadian CT Head Rule (CCHR) and the New Orleans Criteria for Positive Head CT Scan (NOC), have been shown to have high sensitivities and negative predictive values (NPVs) for neurosurgical intervention, but specificities are notably lower.² Because both scoring systems were originally designed to predict the likelihood of a head CT positive for ICH, they consider various clinical characteristics, but do not incorporate any radiographic information from the head CT. Their design and intention also explain why they accurately identify patients who need neurosurgical intervention, but are inaccurate when identifying patients who do not. By using the results from head CTs, alongside clinical factors, it may be possible to more specifically target patients who will need or, maybe more importantly, those who will not need a neurosurgical intervention.

Multiple studies have examined the associations between radiographic characteristics of SDHs and patient outcomes.^{7,12,28,33,38} However, these studies provide Level III evidence, included severe and moderate TBIs, and did not examine neurosurgical intervention as a patient out-

come. Part 1 of this manuscript detailed the association between demographic, clinical, and radiographic characteristics of patients with mTBI and iSDHs, and neurosurgical intervention or nonintervention. The objective of Part 2 of this manuscript was to detail the development of a preliminary clinical decision support tool estimating the probability of receiving a subsequent neurosurgical intervention, to outline the tool's underlying framework and performance, and to discuss its clinical utility.

Methods

The full methods can be found in Part 1 of this study.¹⁹

Study Site and Patient Population

This was a single-center retrospective observational cohort study of adult trauma patients consecutively admitted over 3.5 years at a Level I trauma center. Data were collected through a combination of registry data and chart abstraction. Patients were included if they presented with an mTBI (emergency department [ED] Glasgow Coma Scale (GCS) score 13–15) and had a head CT positive for SDH (ICD-9 852.2–852.39). Patients were excluded from the study if they presented with 1) skull fractures, because the ICH type cannot be determined from skull fracture-related ICD-9 codes; 2) coagulopathy on admission; 3) no acute hemorrhage; 4) a hemorrhage other than an SDH, not including intraventricular hemorrhages (IVHs); 5) no radiological imaging of hemorrhage on admission; or 6) only radiological imaging that was obtained after a neurosurgical procedure. This study was reviewed and approved by the institutional review board and was granted a waiver of consent.

Outcomes and Covariates

The primary outcome of this study was the presence of a neurosurgical procedure (craniotomy/craniectomy/craniostomy, burr hole, catheter drainage of SDH, placement of intracranial pressure monitor, shunt, or ventriculostomy). Covariates were as follows: age, sex, interhospital transfer status, mechanism of injury (fall, motor vehicle accident, and other), ED GCS score, severe head injury (maximum head Abbreviated Injury Scale [AIS] score ≥ 4), Injury Severity Score (ISS 0–15, ≥ 16), normal ED blood pressure (systolic < 120 mm Hg and diastolic < 80 mm Hg), normal ED respiratory rate (12–16 breaths/min), normal ED pulse (60–100 beats/min), normal ED body temperature (36.5°C–37.2°C), normal ED blood oxygen levels (95%–100% saturation), ED disposition, comorbid conditions (obesity, alcoholism, diabetes mellitus, and hypertension), hospital length of stay (days), and hospital disposition.

Radiological Data Abstraction

The following were double-data entered from the electronic medical record for each patient encounter: clinical signs and symptoms (concomitant concussion, nausea, vomiting, headache, dizziness, poor concentration, fatigue, seizures, irritability, rhinorrhea, otorrhea, hemotympanum, raccoon eyes, no pupil response, hypothermia, hy-

poxia, and postinjury loss of consciousness); hemorrhage lobe involvement (falx and tentorial hemorrhages were not assigned a lobe of involvement); presence of acute-on-chronic (AOC) hemorrhage, IVH, mass effect, or midline shift; and hemorrhage status on follow-up CT (obtained from CT reports—completely resolved, resolving, stable, increased, and no follow-up CT). Maximum hemorrhage length and thickness were double—data entered using admission CT or MRI scans; measurements were taken in millimeters and rounded to the nearest tenths' place. If initial imaging was obtained at an outlying facility, measurements were taken from the outlying facility's images. For more information on how double—data entry discrepancies were handled, please see Part 1.¹⁹

Statistical Analysis

Stepwise multivariable logistic regression models were built to analyze the independent association covariates and outcome measures. Entry and exit criteria for these models were 0.20 and 0.15, respectively. The presence of effect modification was examined for all variables included in the final models. Area under the receiver operating characteristic (AUROC) curves and Hosmer-Lemeshow goodness-of-fit statistics are reported for all adjusted logistic regression models; 95% confidence intervals for AUROC curves were calculated using the binomial exact method. Optimal cutoffs for the AUROC curve analysis were determined using MedCalc, version 17.2. All other statistical analyses were 2-tailed and had an alpha value of 0.05; SAS software, version 9.3, was used.

Results

For a more detailed description of the patient population and hematoma characteristics, please see the *Results* section of Part 1.¹⁹ There were 176 patients included in this study. More than half of the patients were 65 years or older, and male. Sixty percent of patients were transferred from an outlying hospital. According to the maximum head AIS score in the ED, 39% suffered a serious head injury; however, 95% had a GCS score of 14 or 15. Ninety-eight percent of non-GCS-15 scores were attributable to a decreased verbal score. Furthermore, almost half of the patients had polytrauma, reflected by an ISS > 15. Hypertension was the most prevalent comorbid condition (52%), > 60% of patients reported headache in the ED, and 39% of patients were reported to have a loss of consciousness after injury. Most patients presented with acute hemorrhages and showed no signs of midline shift, and only 2 patients presented with IVH. Of the 176 patients included in the study, 167 had measured hemorrhages; 9 patients only had tentorial SDHs in which thickness was not measured because of the lack of consistent availability of coronal CT images. The neurosurgical intervention rate in our population with mTBI and iSDH was 15.9%.

The final multivariable logistic regression model created to assess the odds of a neurosurgical intervention included two variables: the maximum thickness of the iSDH, and whether the hematoma was an AOC lesion. The thickness of the hematoma was the most significant variable in the model (Wald $\chi^2 = 18.50$), followed by the

FIG. 1. Graph showing relationship between maximum thickness of mTBI with iSDH, AOC hematoma, and probability of neurosurgical intervention.

AOC variable (Wald $\chi^2 = 2.66$). After adjusting for the presence of an AOC hematoma, for every 1-mm increase in the thickness of the iSDH, the odds of a subsequent neurosurgical procedure increased by 32% (OR 1.32, 95% CI 1.16–1.50).

Based on the beta coefficients for the two covariates in the final model, the equation for determining the probability of requiring a subsequent neurosurgical intervention in our study population was $\text{Risk} = 1 / \{1 + e^{-(-4.9049 + [0.2773 * \text{THICKNESS}] + [0.5615 * \text{AOC}])}\}$. *THICKNESS* is equal to the maximum thickness of the iSDH rounded to the nearest tenth of a millimeter, and *AOC* specifies whether the SDH is an AOC (+1) or not (–1). We created a free online and mobile-friendly calculator for this formula; it can be accessed at <https://jscale.io/calc/A7195rFWw6csVfjy>. Figure 1 depicts the relationship, based on the logistic regression model, between maximum SDH thickness, AOC hemorrhage, and the risk of neurosurgical intervention. In the model, the minimum risk of a neurosurgical intervention for a non-AOC SDH was approximately 0.4%, whereas the minimum risk for an AOC hematoma was 1.3%. An AOC iSDH in the setting of mTBI always resulted in a higher probability of a neurosurgical intervention for any thickness, compared to a non-AOC SDH. According to the model, the largest difference in the probability of a neurosurgical intervention between an AOC and a non-AOC hematoma was observed at a thickness of 18 mm (66% vs 38%), whereas the smallest difference was observed at a thickness of 40 mm (99.9% vs 99.6%). In our actual patient population with mTBI, the smallest iSDH in the neurosurgical intervention group, based on initial presenting CT, was 6.3 mm in thickness.

Figure 2 depicts the distribution of probabilities of neurosurgical intervention for both study groups. Compared to patients who did not have a neurosurgical intervention, those who did displayed a larger variance in probability of neurosurgical intervention (0.12 vs 0.02), with 75% of probabilities ranging between 29% and 99.5%. In contrast,

FIG. 2. Box plot showing distribution of estimated probabilities for neurosurgical intervention by study group. The circles represent observations > 1.5 times the IQR above the 75th percentile.

more than 75% of patients who did not require a neurosurgical intervention had estimated probabilities lower than 6%. The median (IQR) probability of a neurosurgical intervention in the nonneurosurgical intervention group was significantly lower than that in the neurosurgical intervention group (2.3% [1.4%–5.8%] vs 72.8% [28.9%–95.9%]; $p < 0.001$).

Both the discrimination and calibration of the final classification model were excellent, having an AUROC curve of 0.94 (95% CI 0.90–0.97, Fig. 3) and a Hosmer-Lemeshow goodness-of-fit p value of 0.98. According to an AUROC curve analysis, the optimal decision point for determining whether to label a patient as likely to require a neurosurgical intervention was a 9.96% probability of neurosurgical intervention. This decision point resulted in a sensitivity of 93% and a specificity of 83%, and NPVs and positive predictive values (PPVs) of 99% and 45%; the accuracy was 84%. The positive and negative likelihood ratios were 5.38 (95% CI 3.7–7.8) and 0.09 (95% CI 0.02–0.30). Figure 4 demonstrates how the performance of the classification and likelihood ratios changes depending on the decision cutoff value.

In order to maximize the sensitivity of our decision tool, the optimal cutoff point for identifying patients likely to receive a neurosurgical intervention was ≥ 2.25 mm for AOC SDHs and ≥ 6.25 mm for non-AOC SDHs (the corresponding probability of neurosurgical intervention was 2.35% for both of these measures). These cutoffs achieved a sensitivity of 100%, specificity of 53%, and PPV and NPV of 24% and 100%. This decision tool correctly identified 100% of all neurosurgical patients in our study population. Additionally, of all the patients the decision tool labeled as not requiring a neurosurgical intervention, 100% of those patients were in the nonneurosurgical intervention group. The positive and negative likelihood ratios at these cutoffs were 2.1 (95% CI 1.8–2.5) and 0 (100% sensitivity always results in a negative likelihood ratio of 0).

FIG. 3. Graph showing the AUROC curve for predicting neurosurgical intervention. Dotted lines denote the 95% CI for the AUROC curve (black line).

Discussion

In 2002 the European Federation of Neurological Societies recommended that “[t]he primary goal of initial management in mTBI is to identify the patients ... [who] may need neurosurgical intervention.”³⁶ Although more than 15 years has passed, the medical research community has not sufficiently addressed this lingering need.¹⁵ Our study is the first one to use detailed radiographic information about iSDHs in patients with mTBI to develop a preliminary model accurately estimating the probability of a subsequent neurosurgical intervention. Our model showed perfect sensitivity and NPV, and a high specificity, making it a great tool to rule out the likelihood of a neurosurgical intervention for a patient.

There has been little research in the area of predicting neurosurgical intervention in the population with mTBI and ICH.¹⁵ Notwithstanding the low PPV, our model achieved an AUROC curve (0.94) higher than that of many predictive models in the TBI literature that have examined a variety of patient outcomes.^{8,9,21–23,29,32,35,37} Sweeney et al. constructed a predictive model for neurosurgical intervention using more than 50,000 patients with mTBI from the National Trauma Data Bank.³² Because their data were limited to high-level injury information, their model did not include specific quantitative information from head CTs. However, their model achieved an AUROC curve of 0.81, with good calibration. Similar to our own model, their model better identified which patients would not require a neurosurgical intervention than it identified those who would. Although they did not examine neurosurgical interventions, Raj et al. combined the Acute Physiology and Chronic Health Evaluation II (APACHE II) and the International Mission for Prognosis and Analysis of Clinical Trials (IMPACT) scoring systems to pre-

FIG. 4. Graphs showing relationship between classification performance and likelihood ratios, and cutoff criteria for predicting subsequent neurosurgical intervention. LR = likelihood ratio.

dict 6-month mortality in 890 patients with complicated mTBI or moderate to severe TBI; their model achieved an AUROC curve of 0.84.²⁶ Velmahos et al.'s model predicted worsening ICH on routine repeat head CT in 179 patients with mTBI and ICH, with an AUROC curve of 0.83.³⁵ Hukkelhoven and colleagues^{8,9} built a predictive model for 6-month mortality and unfavorable outcome in nearly 2300 patients with moderate to severe TBI; the highest estimate for their AUROC curve was 0.89. We believe the high discrimination power of our model was attributable to the granularity and volume of data collected from head CT images, and by targeting a specific injury type. By collecting hemorrhage thickness and length to an accuracy of one-tenth of a millimeter, in addition to collecting a panoply of hemorrhage characteristics, including AOC bleeding and midline shift, we could assess the importance of each characteristic and retain the variables that best explained the risk of neurosurgical intervention.

The two best-known tools for predicting neurosurgi-

cal intervention in the mTBI population are the NOC and the CCHR, but they are limited in their ability to predict which patients are likely to not require neurosurgical intervention.^{6,31} Because these tools were designed to predict which patients are likely to have positive findings on a head CT, and therefore which patients should receive a head CT, both tools were optimized to have 100% sensitivities for a positive head CT, but for the same reason they have low specificities (3% and 39%) for identifying patients not requiring a neurosurgical intervention.³⁰ Low specificities and perfect sensitivities are useful for predicting which patients should receive a head CT, but if used to predict which patients may or may not require neurosurgical intervention, they improperly inform us that a majority of the population will need the intervention. This limitation is a result of the fact that they were primarily developed to predict which patients should receive a head CT, not which patients may or may not require a neurosurgical intervention; thus, they do not incorporate head CT information.

Once a patient is found to have a head CT positive for ICH, the information from that CT should be used in any model designed to predict the likelihood of neurosurgical intervention. The advantage of our model is that by incorporating these radiological factors we were able to achieve the goal of predicting not only which patients are likely to need neurosurgical intervention, but also (perhaps more importantly) which patients have a very low probability of requiring a neurosurgical intervention. Our final model was able to match the high sensitivity and NPV of the NOC and the CCHR, while also increasing the specificity to 53%. Therefore, not only did our model properly identify all patients who had a neurosurgical intervention, but also it properly identified 53% of the patients who did not have a neurosurgical intervention. This translates into the ability to identify half of all patients who potentially would not require a neurosurgical consultation or transfer to a hospital with neurosurgical capabilities.

Our clinical decision support tool could be used to increase the efficiency with which patients with mTBI and iSDH are managed, ease the demand placed on neurosurgical departments, and more importantly, limit unnecessary transfers from hospitals without neurosurgical coverage to those with neurosurgical capabilities. It has been shown that many neurosurgeons and critical care physicians believe they would improve their practice by using a more accurate prognostic tool for patients with TBI; it is also likely to be true for trauma surgeons and emergency room physicians.²⁵ Furthermore, a national survey of emergency physicians showed that 75% reported inadequate neurosurgical coverage.²⁷ Allowing acute care surgeons to care for a subset of patients with mTBIs and small nonoperative ICHs has been shown to significantly decrease the proportion of neurosurgical consultations while maintaining patient safety.^{10,20} Rather than using semiarbitrary injury measures to determine which eligible patients with mTBIs and ICH can be treated by an acute care surgeon, we believe the decision should be based on the probability of having a neurosurgical intervention. Risk estimation also has a place in telemedicine networks assessing patients with mTBI and ICH. These networks have been repeatedly shown to safely decrease the demand on neurosurgical departments via reduced unnecessary interhospital transfers.^{1,13,14,28} We believe the efficiency of these networks can be increased through the proper estimation of risk for neurosurgical intervention.

Understanding how the thickness of an SDH relates to the risk of neurosurgical intervention is essential when proposing care guidelines. For example, based on our data, a 4-mm-thick SDH can have a risk of neurosurgical intervention of 1.3% or 3.8%, depending on whether it is an AOC hematoma. The Brain Injury Guidelines therapeutic plan for a 4-mm-thick SDH is independent of whether it is an AOC hemorrhage; the plan does not recommend hospital admission, a repeat head CT, or neurosurgical coverage.¹¹ Our results identified the presence of an AOC hematoma as being an independent predictor, and therefore it should be incorporated into an assessment of probability of neurosurgical intervention. It is patently clear that care guidelines targeting proper identification of neurosurgical interventions would benefit from the incorporation of a

quantitative assessment of the risk for neurosurgical intervention.

Perel and colleagues published a systematic review of 102 prognostic models in the TBI population, outlining deficiencies in current models and recommendations for future ones.²⁴ In their publication, calibration was “the most important performance measure for the application of the model in clinical practice.” Our model showed a calibration value of 0.98 (out of 1.00), indicating excellent calibration. Perel et al. also noted the importance of exploring interactions, with only 13% of their reviewed models investigating interactions. Because our model could have included many variables with possible interactions—e.g., hemorrhage length and thickness—we explored many, but found none. Additionally, we aimed to make our decision tool easy to use in the clinical setting. Our tool consists of only two variables, which are easily and rapidly discernible on CT, and we have provided a free, mobile-friendly calculator to illustrate ease of access.

Our study has several limitations. First, our model was created using patients from a single institution across 3.5 years. Therefore, it models the neurosurgical practices of a single institution and may not be representative of neurosurgical practices at other institutions. Variation in surgical practice has been shown, and model creation on small sample sizes can have the potential for overfitting; nevertheless, our models showed excellent discrimination and calibration.^{4,8,34} Also, with 64% of our patients ≥ 65 years of age, our patient population may not be representative of all other trauma centers and therefore may not be fully generalizable across all trauma centers. Additionally, our model has not been externally validated in multiple, independent patient populations. As such, the coefficients in our model are likely to change when validated in a second, independent population. We will execute a validation study in the coming year to confirm the accuracy and validity of this model across multiple trauma centers in the US in the same population of patients with mTBI and iSDH.

Conclusions

Our study has outlined the development of a preliminary clinical decision tool that allows clinicians to estimate the risk of requiring neurosurgical intervention in patients with iSDH and mTBI, based on two variables that are easily available at initial evaluation in the ED: maximum SDH thickness and whether the iSDH is an AOC lesion. Our tool showed excellent sensitivity and NPV, with moderately high specificity, making it a useful tool to rule out the probability of a future neurosurgical intervention. We estimated this tool could reduce the demand for neurosurgical resources by 56% in the study population, ease the strain on scarce neurosurgical staff, decrease hospital costs for patients, and potentially lower the number of unnecessary interhospital transfers.

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Disclosures

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Author Contributions

Conception and design: Orlando, Levy. Acquisition of data: Orlando, Levy. Analysis and interpretation of data: Orlando, Levy, Rubin, Tanner, Lieser. Drafting the article: Bar-Or, Orlando, Levy, Rubin, Carrick, Lieser, Hamilton, Mains. Critically revising

the article: all authors. Reviewed submitted version of manuscript: all authors. Statistical analysis: Orlando. Administrative/technical/material support: Bar-Or, Orlando, Mains. Study supervision: Bar-Or.

Supplemental Information

Companion Papers

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Previous Presentations

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