JOURNAL OF NEUROTRAUMA 37:1269–1282 (June 1, 2020)

DOI: 10.1089/neu.2019.6710

Original Articles

Prognostic Validation of the NINDS Common Data Elements for the Radiologic Reporting of Acute Traumatic Brain Injuries: A CENTER-TBI Study

Thijs Vande Vyvere,[1,2] Ezequiel De La Rosa,[2] Guido Wilms,[2,3] Daan Nieboer,[5] Ewout Steyerberg,[5,6] Andrew I.R. Maas,[4] Jan Verheyden,[2] Luc van den Hauwe,[1] and Paul M. Parizel[1]; CENTER-TBI Participants and Investigators*

Abstract

The aim of this study is to investigate the prognostic value of using the National Institute of Neurological Disorders and Stroke (NINDS) standardized imaging-based pathoanatomic descriptors for the evaluation and reporting of acute traumatic brain injury (TBI) lesions. For a total of 3392 patients (2244 males and 1148 females, median age = 51 years) enrolled in the Collaborative European NeuroTrauma Effectiveness Research in Traumatic Brain Injury (CENTER-TBI) study, we extracted 96 Common Data Elements (CDEs) from the structured reports, spanning all three levels of pathoanatomic information (i.e., 20 ''basic,'' 60 ''descriptive,'' and 16 ''advanced'' CDE variables per patient). Six-month clinical outcome scores were dichotomized into favorable (Glasgow Outcome Scale Extended [GOS-E] = 5-8) versus unfavorable (GOS-E = 1-4). Regularized logistic regression models were constructed and compared using the optimism-corrected area under the curve (AUC). An abnormality was reported for the majority of patients (64.51%). In 79.11% of those patients, there was at least one coexisting pathoanatomic lesion or associated finding. An increase in lesion severity, laterality, and volume was associated with more unfavorable outcomes. Compared with the full set of pathoanatomic descriptors (i.e., all three categories of information), reporting ''basic'' CDE information provides at least equal discrimination between patients with favorable versus unfavorable outcome (AUC = 0.8121 vs. 0.8155, respectively). Addition of a selected subset of ''descriptive'' detail to the basic CDEs could improve outcome prediction (AUC = 0.8248). Addition of ''advanced'' or ''emerging/exploratory'' information had minimal prognostic value. Our results show that the NINDS standardized-imaging based pathoanatomic descriptors can be used in large-scale studies and provide important insights into acute TBI lesion patterns. When used in clinical predictive models, they can provide excellent discrimination between patients with favorable and unfavorable 6-month outcomes. If further validated, our findings could support the development of structured and itemized templates in routine clinical radiology.

Keywords: Common Data Elements; computed tomography; structured reporting; traumatic brain injury

Introduction

Traumatic Brain Injury (TBI) encompasses a vast spectrum of acute pathoanatomic lesions.[1,2] Evaluation of these lesions on non-contrast computed tomography (NCCT) scans is often complex and challenging, and has been associated with significant observer error and variability.[3,4] Moreover, substantial differences exist in how lesions are reported and classified, even between expert neuroradiologists.[3] Terminology also may differ between various medical disciplines, which makes it difficult to compare data from clinical trials or studies.[2]

In order to minimize these observer differences, to facilitate clinical effectiveness research, data sharing, data aggregation for registries, data interoperability, and the development and testing of

[1]Department of Radiology, University Hospital and University of Antwerp, Antwerp, Belgium.
[2]Icometrix, Research and Development, Leuven, Belgium.
[3]Department of Radiology, University Hospital Leuven and Catholic University of Leuven, Leuven, Belgium.
[4]Department of Neurosurgery, Antwerp University Hospital and University of Antwerp, Antwerp, Belgium.
[5]Center for Medical Decision Making, Department of Public Health, Erasmus Medical Center, Rotterdam, the Netherlands.
[6]Department of Biomedical Data Sciences, Leiden University Medical Center, Leiden, the Netherlands.
*CENTER-TBI participants and investigators are listed at the end of the article.

computerized models, multiple instances have advocated a more standardized way to evaluate and report TBI lesions.[2,5] One way to achieve this is by using consistent language in the form of Common Data Elements (CDEs). CDEs are logical units of data that are clearly conceptualized by definitions and can be used across different studies.

In 2010, a consortium of TBI experts from the National Institutes of Health and National Institute for Neurological Disorders and Stroke (NINDS) created a set of radiologic CDEs, which includes controlled terms and standardized definitions to characterize the different types of pathoanatomic lesions encountered on imaging of TBI patients.[2,6] Information pertaining to these lesions can be classified into three levels of successive detail: 1) ''basic'' or ''supplemental–highly recommended'' information (presence vs. absence); 2) ''descriptive'' or ''supplemental'' information (location, size, extent, etc.); and 3) ''advanced'' or ''emerging/exploratory'' information (subtype, quantitative volumetry, etc.).[2,6]

Several large-scale multi-center TBI studies have implemented this kind of standardized and structured CDE characterization.[7,8] Research shows that good interobserver and intraobserver agreement can be achieved for the reporting of ''basic'' data elements.[9,10] However, the value and prognostic importance of reporting these different pathoanatomic descriptors has not been extensively investigated. For example, the majority of ''descriptive'' and ''advanced'' data elements have not been fully validated or correlated with clinical outcome.[6] A thorough prognostic validation is therefore urgently needed.

The main purpose of this study is to investigate the value of using the recommended NINDS standardized pathoanatomic terms and definitions for reporting acute TBI lesions. More specifically, we aim to explore acute NCCT lesion patterns and to investigate the prognostic value of the different pathoanatomic descriptors by building regularized logistic regression models that cover all successive levels of lesion information.

Methods

Study design, setting, and ethics statement

The Collaborative European NeuroTrauma Effectiveness Research in Traumatic Brain Injury (CENTER-TBI) project included a multi-center longitudinal and observational study (registered at ClinicalTrials.gov: NCT02210221).[8] Patients with a clinical diagnosis of TBI and an indication for CT scanning were enrolled in three strata, differentiated by care path (i.e., emergency room [ER], admission, or intensive care unit [ICU] stratum). The study protocol was approved by the national and local ethics committees for each participating center. Informed consent, including use of data for other research purposes, was obtained in each subject according to local regulations. Patient data was de-identified and coded by means of a Global Unique Patient Identifier.

NCCT evaluation

A total of 4037 initial NCCT scans, from 55 different European centers, were forwarded to a centralized imaging repository and evaluated by a central review panel between January 2015 and December 2018. The review panel consisted of three protocol-trained reviewers (i.e., one expert neuroradiologist with over 25 years of experience and two trained neuroscientists with expertise in radiologic neuroanatomy). All readers were blinded to clinical patient information, except for gender, age, and care path stratum. Pathoanatomic data elements were evaluated and entered directly into digital custom-made multi-tiered structured templates (Fig. 1 for an example). Each synoptic report was generated as a draft by one of the two neuroscientists, followed by a double-reading and validation by the expert neuroradiologist.

NINDS TBI CDEs

A total of 96 CDEs (20 ''basic,'' 60 ''descriptive,'' and 16 ''advanced'') were extracted from the synoptic reports for this study. Three variables, that were not clearly defined in the NINDS CDEs, were evaluated extra and incorporated in the study as ''descriptive'' or ''supplemental'' pathoanatomic descriptors (i.e., total lesion volume, herniation, and pre-existing lesions). Three-dimensional skull reconstructions were made to evaluate fractures for each patient. Midline shift was measured using the A/2–B method,[11] and reported when higher than 5 mm. Volume estimations for hematomas and contusions were performed using the $A \times B \times C/2$ method, where A is the width, B is the depth, and C is the length of the lesion.[12] Pericontusional edema was included in the lesion measurements. For this study, where possible, location variables were simplified by collapsing them into unilateral or bilateral (Supplementary Tables S1-S3).

Outcome and final dataset

For 3392 of the 4037 reviewed patients (84%), the 6-month outcome (GOS-E) score was retrieved from the CENTER-TBI core dataset via the Neurobot© platform (International Neuroinformatics Coordinating Facility [INCF], version 1.2). Outcome scores were dichotomized (i.e., favorable outcome: GOS-E = 5-8, unfavorable outcome: GOS-E = 1–4), in accordance with previous studies.[13,14] Venous sinus injury was rarely reported. Unfortunately, when reported, no outcome data was available. This resulted in 19 ''basic'' CDEs and a total of 95 predictor variables for regression analysis.

Statistical analysis

Descriptive statistics. Descriptive statistics were used to analyze patient demographics and lesion frequencies. Age between patients with favorable versus unfavorable outcome was compared using the Student's t-test. Gender distribution was examined using the chi-squared test. Non-parametric Mann-Whitney U tests were performed to investigate differences in the median volume of lesions.

Regularized logistic regression. To reduce the complexity of our large set of variables and to have an optimal performing model with low variance, regularized logistic regression was used. Before building the models, continuous and categorical variables were scaled by dividing by two times the standard deviation.[15] Two base ridge regression models were built: 1) one with the full set of CDEs (CDE_{full}) and 2) one with only ''basic'' or ''supplemental–highly recommended'' CDEs (CDE_{basic}). Ridge regression is a form of regularized regression where a penalty is imposed to the model for having too many variables. Regression coefficients of the variables that are less contributive are typically shrunk toward, but not equal to, zero. They are penalized but stay in the model. Least Absolute Shrinkage and Selection Operator (LASSO) regression is another regularized regression technique that shrinks coefficients of less contributing variables exactly to zero.[16] In contrast to ridge regression, this technique reduces a large set of variables to only the important ones by performing variable or feature selection. The penalty that is given to the variables in regularized regression models is controlled by two hyperparameters: 1) lambda (λ), which accounts for the amount of regularization used in the model and 2) alpha (α), which accounts for the relative importance of the L1 (LASSO) and L2 (ridge) regularizations (i.e., ridge regression $\alpha = 0$; LASSO regression $\alpha = 1$). Addressing the expected multicollinearity in our data, we constructed four models with elastic net penalties, which uses both ridge and LASSO (i.e., $0 < \alpha < 1$) regularization.[17] This shrinks some regression coefficients and others

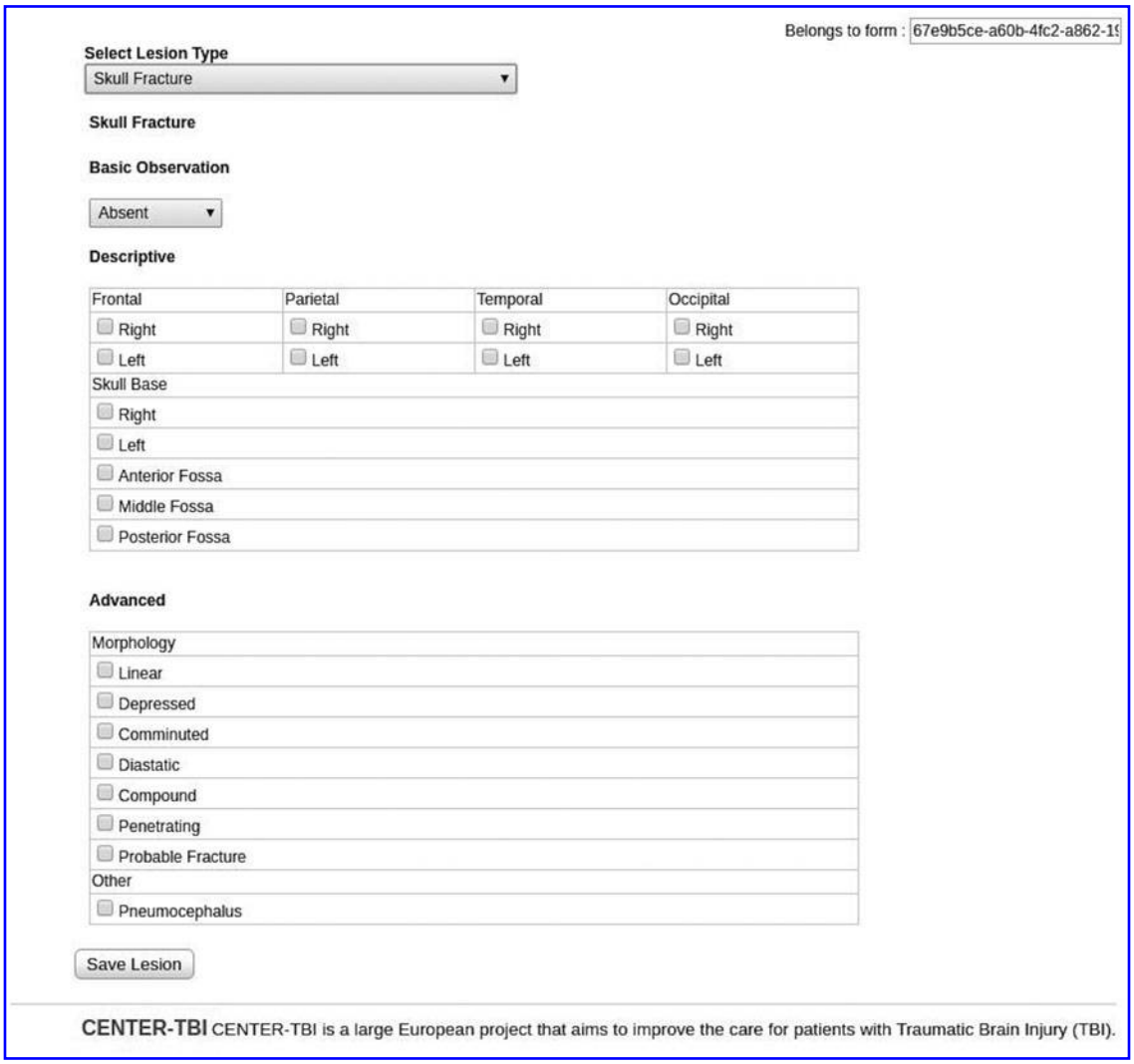

FIG. 1. Example of a structured and itemized template (i.e., for skull fracture), used for standardized evaluation and reporting in the Collaborative European NeuroTrauma Effectiveness Research in Traumatic Brain Injury (CENTER-TBI) study. The ''basic'' or ''supplemental–highly recommended'' tier refers to the presence or absence of an abnormality. The ''descriptive'' or ''supplemental'' tier gives more details about the location or volume. The ''advanced'' or ''emerging/exploratory'' tier gives extra information about the nature of the lesion or involves an emerging technique.

are set exactly to zero. Elastic net regression typically performs better than LASSO regression in the presence of highly correlated predictors[17] (see Table 1 for model characteristics). For all models, hyperparameters were chosen using 10×10 cross-validation. The stability of the variable selection procedure and the optimism-corrected performance of the models was assessed in a 100-repetition bootstrap resampling procedure.[18]

Results

Descriptive statistics

Our dataset consisted of 2244 males (66.20%) and 1148 females (33.80%), with a median age of 51 (0–96 years). A total of 818 patients had unfavorable outcome (24%), for which no gender

TABLE 1. MODEL CHARACTERISTICS

#	*Model*	*Input CDEs* N(%)	*Regression*	*Selection characteristics*
1	CDE_{full}	95 (100%)	Ridge	Base model: Shrinkage of regression coefficients, no variable selection
2	CDE_{basic}	19 (20%)	Ridge	Base model: Shrinkage of regression coefficients, no variable selection
3	$CDE_{basic'}$	19 (20%)	Elastic Net	Subset selection on basic variables
4	$CDE_{basic+descriptive}$	79 (83%)	Elastic Net	Subset selection on descriptive variables, basic CDEs not penalized
5	$CDE_{basic+advanced}$	35 (37%)	Elastic Net	Subset selection on advanced variables, basic CDEs not penalized
6	$CDE_{basic+descriptive+advanced}$	95 (100%)	Elastic net	Subset selection on descriptive and advanced variables, basic CDEs not penalized

CDE, Common Data Element.

differences were found ($\chi^2 = 0.025$, $p = 0.8755$). However, patients with unfavorable outcome were older (mean = 58.1 vs. 46.4; $p < 0.0001$). Of all patients, 691 were in the ER (20,4%), 1133 were admitted to the ward (33,4%) and 1568 were in the ICU (46%).

Pathoanatomic lesion frequency and co-occurrence

An abnormality was reported for the majority of patients (64.51%). If a skull fracture was present, patients had an intracranial abnormality in 92% of cases. The most common acute finding was traumatic subarachnoid hemorrhage (tSAH; 46.55%), followed by skull fracture (38.33%), contusion (33.31%), and acute subdural hematoma (SDH; 29.83%; Fig. 2). When an abnormality was found on the initial NCCT scan, in 79.11% of the cases there was at least one co-existing pathoanatomic lesion or associated finding. In many patients, the most common co-existing pathoanatomic lesion types were skull fractures with tSAH (28.50% of patients), contusions with tSAH (27.30% of patients), skull fractures and contusion (24.20% of patients), and acute SDH with tSAH (23.20% of patients; Fig. 3).

Pathoanatomic lesion laterality

Compared with unilateral lesions, bilateral lesions were associated more with unfavorable outcome (e.g., bilateral vs. unilateral acute subdural hematoma, 67.60% vs. 38%; bilateral vs. unilateral frontal contusion, 51.20% vs. 33.90%; bilateral vs. unilateral parietal contusion, 80.0% vs. 52.60%; bilateral vs. unilateral contusion of the basal ganglia, 80.0% vs. 66.70%; and bilateral vs. unilateral axonal injury in the genu of the corpus callosum, 100.0% vs. 46.20%).

Pathoanatomic lesion severity

An increase in the amount of tSAH was associated with more unfavorable outcome (basal cistern trace: 51.50% vs. moderate: 61.90% vs. full: 83.70%; bilateral cortical trace: 43.30% vs. moderate 66.20% vs. full 81.60%). A higher degree of compression of the cisterns also was more associated with unfavorable outcome (compressed vs. obliterated suprasellar cistern: 60.60% vs. 85.40%, quadrigeminal cistern: 63.60% vs. 82.60%, ambient cistern: 57.20% vs. 83.10%, cerebellomedullary cistern: 71.80% vs. 87%).

Pathoanatomic lesion volumes

For specific lesion types, the median volumes were significantly higher in patients with unfavorable outcome than in patients with favorable outcome (i.e., total lesion volume: 43.14 vs. 8.59 mL, $p < 0.0001$; acute subdural hematoma volume: 31.48 vs. 10.92 mL, $p < 0.0001$; and contusion volume: median = 11.420 vs. 3.005 mL, $p < 0.0001$). The differences between other extra-axial bleedings were not significant (i.e., median epidural hematoma volume: 5.98 vs. = 4.38 mL, $p = 0.2417$; mixed subdural hematoma: 41.84 vs. 27.51 mL, $p = 0.43$ extra-axial hematoma: 3.62 vs.

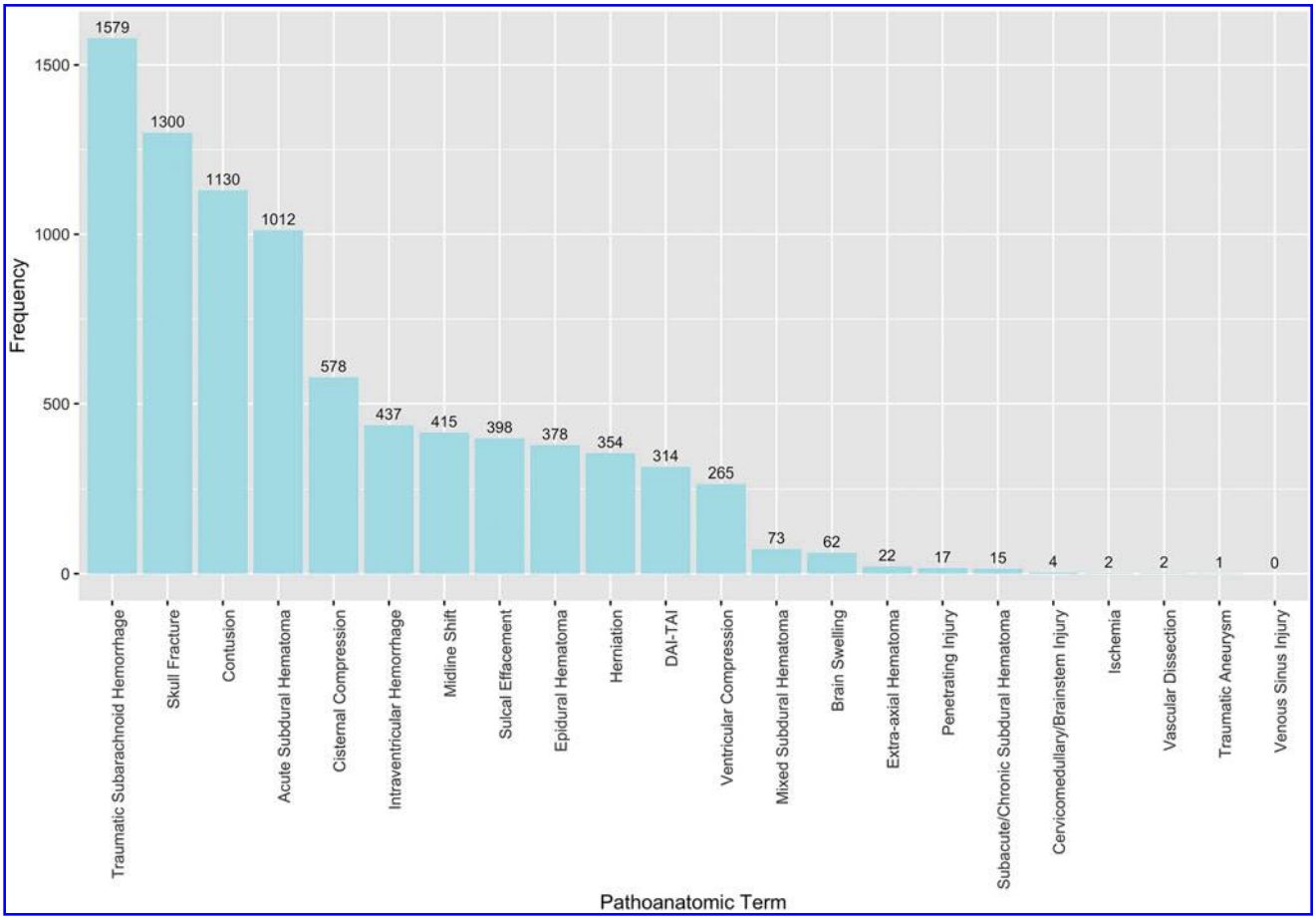

FIG. 2. Frequencies of different ''basic'' pathoanatomic lesion types encountered on the initial non-contrast computed tomography of a subset of 3392 patients, enrolled in the Collaborative European NeuroTrauma Effectiveness Research in Traumatic Brain Injury (CENTER-TBI) study.

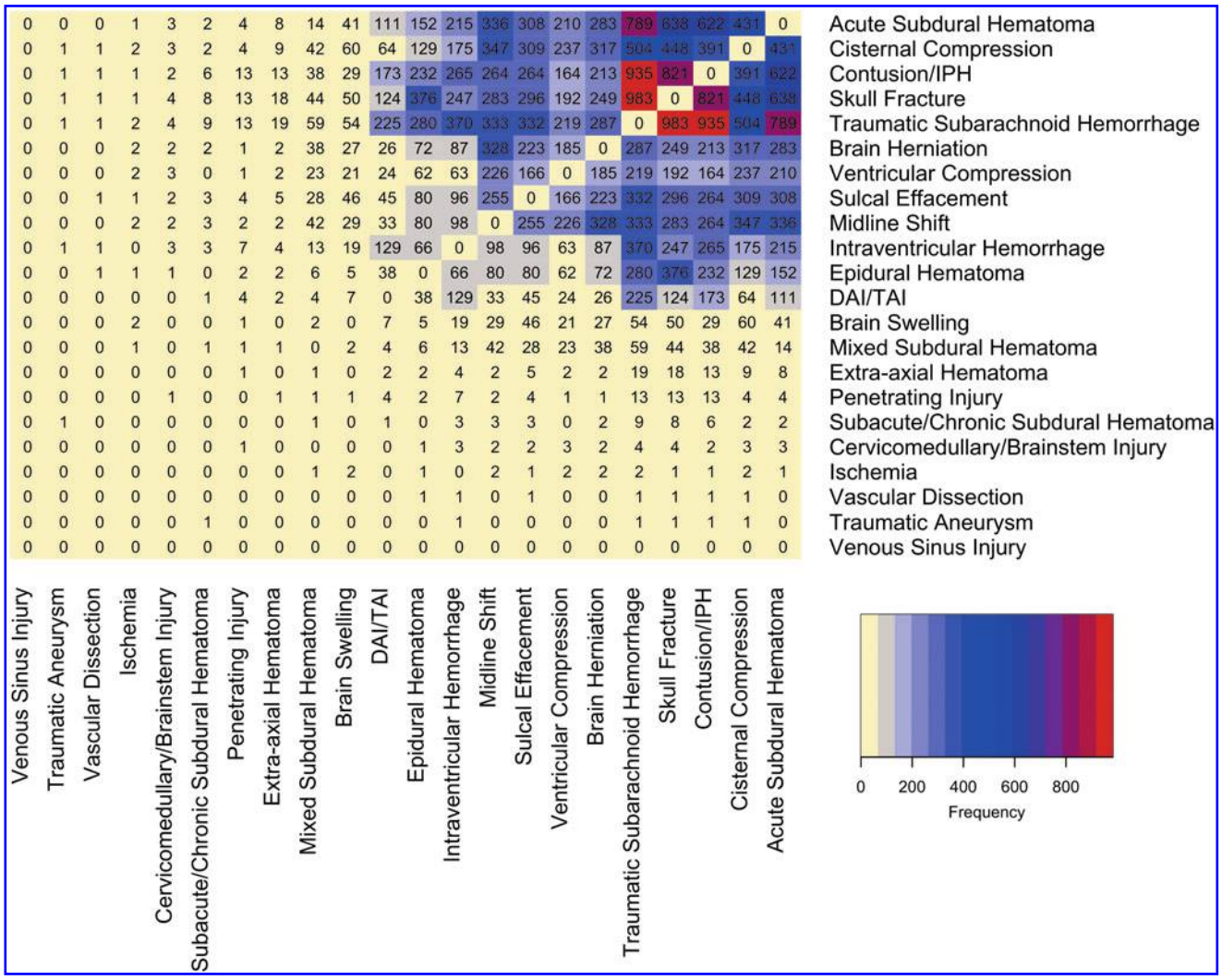

FIG. 3. Co-occurrence matrix of different ''basic'' pathoanatomic lesion types encountered on the initial non-contrast computed tomography of a subset of 3392 patients, enrolled in the Collaborative European NeuroTrauma Effectiveness Research in Traumatic Brain Injury (CENTER-TBI) study.

0.90 mL, $p = 0.11$; and chronic/subacute subdural hematoma: 12.10 vs. 19.64 mL, $p = 0.46$).

Regularized logistic regression

Base models. Table 2 shows the optimism-corrected area under the receiver operating characteristic curve and corresponding confidence intervals for the different logistic regression models. Applying ridge regression to the full set of CDEs (CDE_{full}) yielded good discrimination between patients with favorable versus unfavorable outcome (area under the curve [AUC] = 0.8121). Applying ridge regression to the ''basic'' CDEs only (CDE_{basic}), yielded a slightly higher discrimination (AUC = 0.8155). Mean regression coefficients of the bootstrapped samples for the ''basic'' CDEs are shown in

TABLE 2. MODEL PERFORMANCE AND FREQUENCY OF SELECTED VARIABLES

#	*Model*	*Regression*	*Input CDEs (N, Overall %)*	*Selected CDEs (N, Overall %)**	*Optimism corrected AUROC (95% CI)*
1	CDE_{full}	Ridge	95 (100%)	95 (100%)	0.8121 (0.8031–0.8179)
2	CDE_{basic}	Ridge	19 (20%)	19 (20%)	0.8155 (0.8086–0.8203)
3	$CDE_{basic'}$	Elastic Net	19 (20%)	15 (16%)	0.8169 (0.8057–0.8182)
4	$CDE_{basic+descriptive}$	Elastic Net	79 (83%)	48 (51%)	0.8248 (0.8177–0.8361)
5	$CDE_{basic+advanced}$	Elastic Net	35 (37%)	28 (30%)	0.8179 (0.8107–0.8232)
6	$CDE_{basic+descriptive+advanced}$	Elastic net	95 (100%)	61 (64%)	0.8010 (0.7827–0.8161)

*Median selected CDEs during bootstrapping. For $CDE_{basic+descriptive}$, $CDE_{basic+advanced}$ and $CDE_{basic+descriptive+advanced}$, 19 basic CDEs were kept fixed in the models.

CDE, Common Data Element; AUROC, area under the receiver operating characteristic curve; CI, confidence interval.

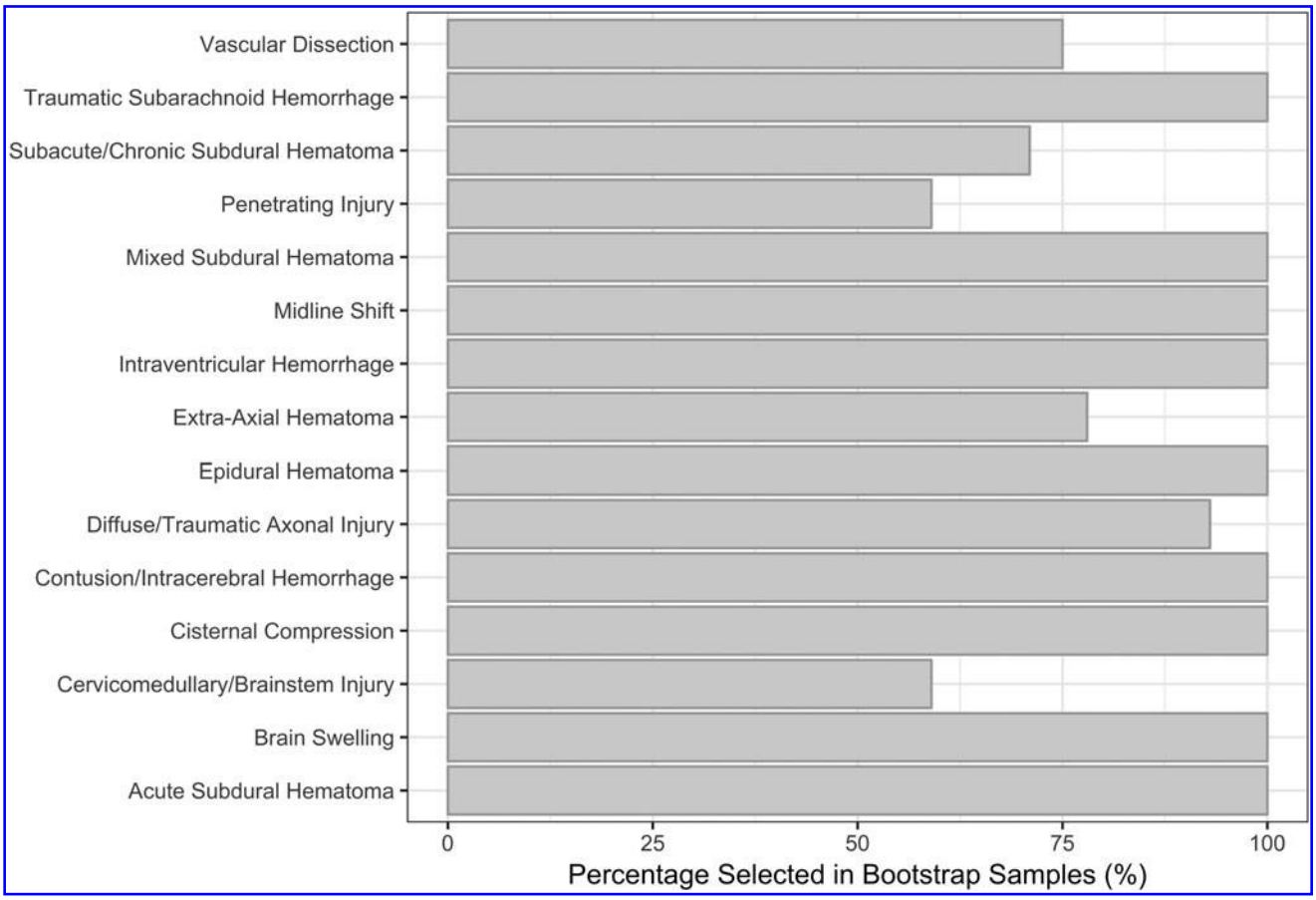

FIG. 4. Percentage of ''basic'' Common Data Elements (CDEs) selected during the optimism-corrected bootstrapping procedure for the CDE_{basic}' model. Note: only variables are shown that were selected in at least 50% of the bootstrap samples.

Supplementary Table S4, indicating substantial prognostic importance of vascular injury, ischemia, brain swelling, subdural hematoma, intraventricular hemorrhage, cisternal compression and tSAH.

Variable selection and selection stability of elastic net models. Table 2 shows the total frequency of retained pathoanatomic variables in the different elastic net models. During bootstrapping of the CDE_{basic}' model, a median of 15 out of 19 variables were selected in at least 50% of the bootstrap samples (Fig. 4). Traumatic aneurysm, ischemia, skull fracture, and ventricular compression were not commonly selected (i.e., <50%). Compared with the base models, the CDEbasic' model slightly increased discrimination (Table 2).

The ''basic'' pathoanatomic data elements were further kept fixed in the elastic net models by not penalizing them and variable selection was performed only on the ''descriptive'' and ''advanced'' information. During bootstrapping of the $CDE_{basic+descriptive}$ model, a median of 29 out of 61 ''descriptive'' variables were selected in at least 50% of the bootstrap samples (Table 2). For the $CDE_{basic+descriptive+advanced}$ model, a median of 34 out of 61 ''descriptive'' variables were selected in at least 50% of the bootstrap samples (Table 2), of which 28 variables were co-selected in both models (Fig. 5A).

During bootstrapping of the $CDE_{advanced}$ model, a median of nine of 16 variables were selected in at least 50% of the bootstrap samples. For the $CDE_{basic+descriptive+advanced}$ model, a median of eight of 16 ''advanced'' variables were selected, of which all 8 were co-selected in both models (Fig. 5B). The $CDE_{advanced}$ model slightly increased the AUC, but adding ''advanced'' descriptors to the ''basic'' and ''descriptive'' information performed worse than the base models (Table 2). The best classification performance was achieved by the $CDE_{basic+descriptive}$ model (Table 2). Table 3 shows the CDEs, with successive levels of detail, that were selected by the original models.

Discussion

Our study is the first large-scale effort to investigate the value of using NINDS standardized pathoanatomic terms and definitions for the evaluation and reporting of acute TBI lesions. Our findings show that this kind of structured CDE characterization, with multiple levels of lesion detail, can be used in large-scale studies and can provide important insights into common and uncommon lesion patterns. For instance, we confirm the expectation that most TBI patients with a lesion on the initial NCCT scan, have co-existing pathology,[6] and that certain pathoanatomic entities tend to co-occur.

Our study also indicates that standardized imaging-based pathoanatomic descriptors can be used to build strong clinical predictive models. In particular, we illustrated that regularized logistic regression models, using acute NCCT-based pathoanatomic data elements as predictors, can provide excellent discrimination between patients with favorable and unfavorable outcomes after TBI. Interestingly, however, the greatest amount of prognostic information was provided by ''supplemental–highly recommended'' or ''basic'' data elements (i.e., presence or absence of lesions), which corroborates this set of pathoanatomic terms as essential imaging elements for clinical studies.

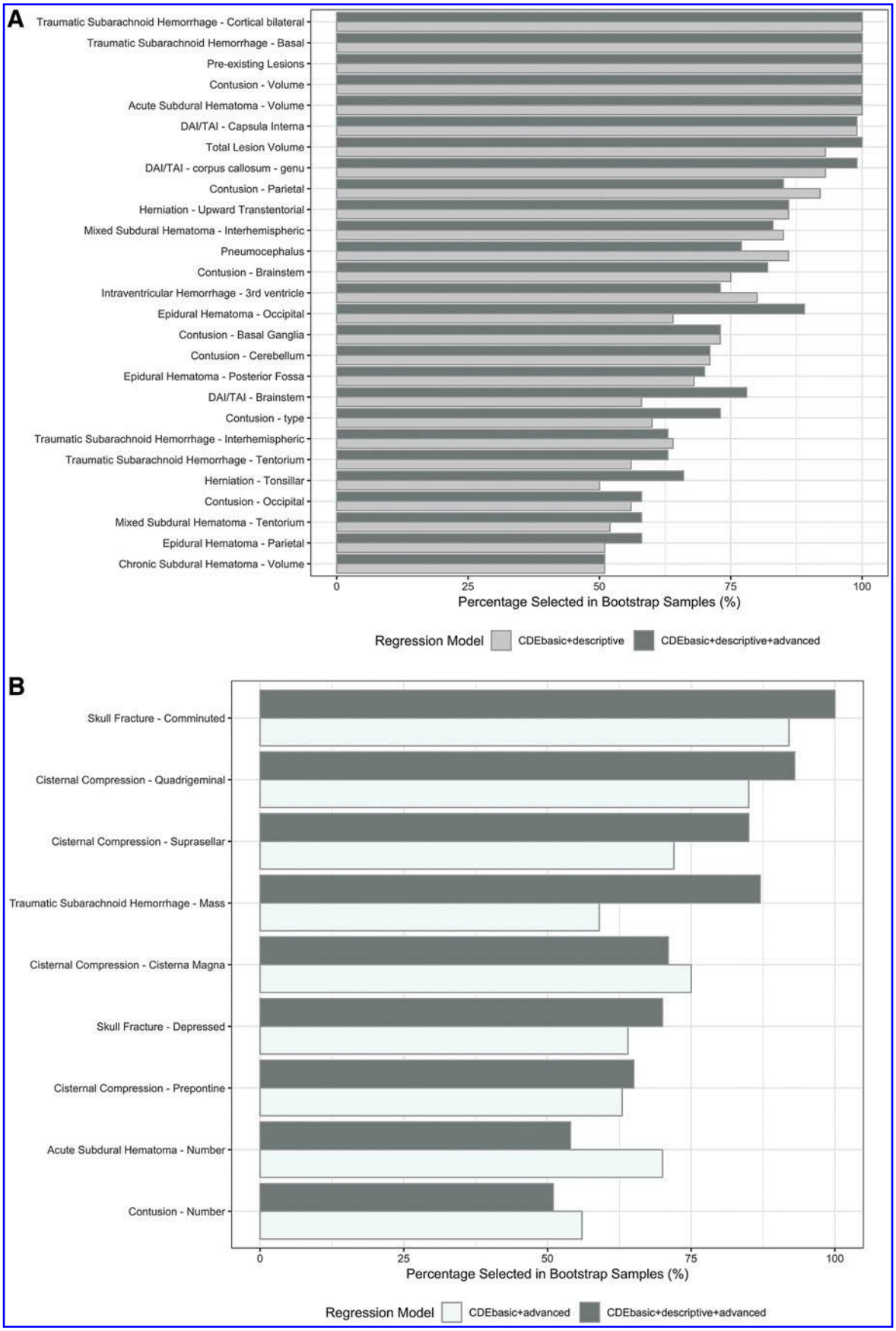

FIG. 5. **(A)** Percentage of ''descriptive'' variables selected during the optimism-corrected bootstrapping procedure for the Common Data Elements $(CDE)_{basic+descriptive}$ and $CDE_{basic+descriptive+advanced}$ models. **(B)** Percentage of ''advanced'' variables selected during the optimism-corrected bootstrapping procedure for the $CDE_{basic+advanced}$ and the $CDE_{basic+descriptive+advanced}$ models. Note: Only variables are shown that were selected in at least 50% of the bootstrap samples and were co-selected by both models.

Table 3. Selected CDE Variables by the Original Elastic Net Regression Models

	Basic CDEs		*Descriptive information*		*Advanced information*	
#	CDE_{basic}	$CDE_{basic'}$	$CDE_{basic+descriptive}$	$CDE_{basic+descriptive+advanced}$	$CDE_{basic+advanced}$	$CDE_{basic+descriptive+advanced}$
1	Skull fracture	-	Pneumocephalus	-	Comminuted, depressed	Comminuted
2	Extra-axial hematoma	+	-	-	-	-
3	Epidural hematoma	+	Parietal, Occipital	-	-	-
4	Subdural hematoma, acute	+	Volume	Volume	Number	-
5	Subdural hematoma, subacute/chronic.	+	-	-	-	-
6	Subdural hematoma, mixed	+	Tentorium, Interhemispheric	Tentorium, Interhemispheric	-	-
7	Traumatic subarachnoid hemorrhage	+	Basal, cortical bilateral, Tentorium, Interhemispheric	Basal, cortical bilateral, Interhemispheric	Mass, size	Mass
8	Vascular dissection	+	-	-	-	-
9	Traumatic aneurysm	-	-	-	-	-
10	Venous sinus injury	-	-	-	-	-
11	MLS	+	-	-	-	-
12	Cisternal compression	+	-	-	Suprasellar, prepontine, quadrigeminal, cerebellomedullary	Suprasellar, prepontine, quadrigeminal
13	Ventricular Compression	-	-	-		-
14	Contusion	+	Type, parietal, occipital, basal ganglia, brainstem, volume	Type, parietal, basal ganglia, volume	Number	-
15	Intraventricular Hemorrhage	+	3rd ventricle	-	-	-
16	TAI/DAI	+	Corpus callosum (genu), Capsula interna, brainstem	Corpus callosum (genu), capsula interna	-	-
17	Penetrating Injuries	+	-	-	-	-
18	Cervicomedullary junction/Brainstem Injury	+	-	-	-	-
19	Ischemia	+	-	-	-	-
20	Brain Swelling	+	-	-	-	-
Extra	Herniation		Upward transtentorial	Upward transtentorial		
Extra	Incidental findings		Pre-existing lesions Total lesion volume	Pre-existing lesions Total lesion volume		

CDE, Common Data Element; MLS, midline shift.

Nevertheless, the best prognostic model in our study contained a subset of selected ''descriptive'' or ''supplemental'' data elements added to the ''basic'' information. More specifically, distinct locations, laterality, and volumes of certain pathoanatomic entities improved discrimination performance. For example, tSAH location, laterality and degree was consistently selected, together with the volume of acute subdural hematomas, contusions, and the presence of pre-existing lesions. Traumatic axonal injuries (i.e., capsula interna, genu of the corpus callosum and brainstem) location and, among others, the sum of all estimated lesion sizes (i.e., total lesion volume) also provided important prognostic information. These findings are very much in line with previous studies.[19–24]

Interestingly, however, the majority of ''descriptive'' and ''advanced'' data elements were extraneous to predict good or bad outcome in our study. One possible explanation for this finding is that certain details are redundant for dichotomized GOS-E outcomes. For example, in many cases when cisternal compression is reported, multiple cisterns are compressed simultaneously, which may render this extra information redundant. However, these details might be relevant for other outcomes of interest.

The call for using standardized language in clinical radiology routine is also growing.[25] Unfortunately, radiologists still report TBI lesions using unstructured narrative free-text and are known to underreport volumes in clinical routine.[26] In addition, more than a

third of neurosurgeons solely rely on visual intuition for their surgical decision-making, despite volume-based surgical and patient management recommendations and guidelines.[27,24]

Radiologists often argue that that structured reporting systems, using a standardized lexicon, might diminish efficiency, reduce the speed of reporting and cause too much distraction in a field with broad pathology. However, our study indicates that ''basic'' or ''supplemental–highly recommended'' pathoanatomic terms, as recommended by the NINDS working group, offer an essential framework of strong outcome predictors that can be incorporated in itemized structured reporting templates. Important details (i.e., volume and location) can be added, based on the clinical or prognostic question of the treatment team. Moreover, automatic quantification of lesion volume is already within reach.[28] Not only has this shown to improve prognostic models,[29] it could offer a more complete, objective and consistent evaluation of TBI lesions in radiology routine. More ''advanced'' or ''emerging/ exploratory' techniques are currently under validation. When incorporated into CDE-based reporting, they could help improve the standardization of clinical decision-making and treatment of acute TBI patients.

We acknowledge several limitations to our study. For example, proportional odds regression might offer some efficiency gains compared with conventional binary logistic regression with GOS-E.[30] However, regularized logistic regression with elastic net penalties is a statistically robust method for variable selection and was optimally suited for our study. Another limitation is that some variables (i.e., vascular injuries and venous sinus injury) were seldomly reported. These injuries are rare and their diagnosis is difficult to make based on NCCT imaging alone, without CT angiography or venography to confirm. In our study, CT angiograms were rarely uploaded. Unfortunately, of those reported, outcome data was not always present. In the future, an increased sample size of these data elements and the incorporation of other imaging modalities (magnetic resonance imaging [MRI], CT- angiography or venography, etc.) could reveal other important descriptors. Finally, our work focusses only on the initial NCCT. Certain secondary injuries (e.g., ischemia, swelling, etc.) are often only detected on a follow-up NCCT scan. We did not include or investigate CDEs that are related to follow-up (e.g., brain atrophy, lesion volume change) or more ''advanced'' and ''emerging/ exploratory'' neuroimaging techniques (diffusion tensor imaging, etc.). Future studies might address these questions, in addition to investigating the value of using standardized imaging-based pathoanatomic data elements in predicting neuro-worsening, or changes in patient status, that might need specific interventions to improve clinical outcome.

Conclusion

Our study represents the first large-scale effort to scientifically vet the NINDS pathoanatomic terms and definitions for the reporting of acute TBI lesions. We show that these standardized-imaging based pathoanatomic descriptors can be used in large-scale studies and provide important insights into common and uncommon acute lesion patterns. When incorporated in clinical prediction models, specific standardized NCCT-based data elements can offer excellent discrimination between patients with favorable and unfavorable 6-month outcomes after TBI. Further validation of our findings can also support the development of consensus-based itemized templates for structured reporting of TBI lesions in clinical radiology routine.

The CENTER-TBI Participants and Investigators

Cecilia Åkerlund, Department of Physiology and Pharmacology, Section of Perioperative Medicine and Intensive Care, Karolinska Institutet, Stockholm, Sweden; Krisztina Amrein, János Szentágothai Research Center, University of Pécs, Pécs, Hungary; Nada Andelic, Division of Surgery and Clinical Neuroscience, Department of Physical Medicine and Rehabilitation, Oslo University Hospital and University of Oslo, Oslo, Norway; Lasse Andreassen, Department of Neurosurgery, University Hospital Northern Norway, Tromso, Norway; Audny Anke, Department of Physical Medicine and Rehabilitation, University Hospital Northern Norway, Tromso, Norway; Anna Antoni, Trauma Surgery, Medical University Vienna, Vienna, Austria; Gérard Audibert, Department of Anesthesiology and Intensive Care, University Hospital Nancy, Nancy, France; Philippe Azouvi, Raymond Poincare hospital, Assistance Publique—Hopitaux de Paris, Paris, France; Maria Luisa Azzolini, Department of Anesthesiology and Intensive Care, S Raffaele University Hospital, Milan, Italy; Ronald Bartels, Department of Neurosurgery, Radboud University Medical Center, Nijmegen, the Netherlands; Pál Barzó, Department of Neurosurgery, University of Szeged, Szeged, Hungary; Romuald Beauvais, International Projects Management, ARTTIC, Munchen, Germany; Ronny Beer, Department of Neurology, Neurological Intensive Care Unit, Medical University of Innsbruck, Innsbruck, Austria; Bo-Michael Bellander, Department of Neurosurgery and Anesthesia and Intensive Care Medicine, Karolinska University Hospital, Stockholm, Sweden; Antonio Belli, NIHR Surgical Reconstruction and Microbiology Research Center, Birmingham, United Kingdom; Habib Benali, Anesthesie-Réanimation, Assistance Publique—Hopitaux de Paris, Paris, France; Maurizio Berardino, Department of Anesthesia and ICU, AOU Città della Salute e della Scienza di Torino—Orthopedic and Trauma Center, Torino, Italy; Luigi Beretta, Department of Anesthesiology and Intensive Care, S Raffaele University Hospital, Milan, Italy; Morten Blaabjerg, Department of Neurology, Odense University Hospital, Odense, Denmark; Peter Bragge, BehaviourWorks Australia, Monash Sustainability Institute, Monash University, Victoria, Australia; Alexandra Brazinova, Department of Public Health, Faculty of Health Sciences and Social Work, Trnava University, Trnava, Slovakia; Vibeke Brinck, Quesgen Systems Inc., Burlingame, California; Joanne Brooker, Australian and New Zealand Intensive Care Research Center, Department of Epidemiology and Preventive Medicine, School of Public Health and Preventive Medicine, Monash University, Melbourne, Australia; Camilla Brorsson, Department of Surgery and Perioperative Science, Umeå University, Umeå, Sweden; Andras Buki, Department of Neurosurgery, Medical School, University of Pécs, Hungary and Neurotrauma Research Group, János Szentágothai Research Center, University of Pécs, Hungary; Monika Bullinger, Department of Medical Psychology, Universitätsklinikum Hamburg-Eppendorf, Hamburg, Germany; Manuel Cabeleira, Brain Physics Lab, Division of Neurosurgery, Department of Clinical Neurosciences, University of Cambridge, Addenbrooke's Hospital, Cambridge, United Kingdom; Alessio Caccioppola, Neuro ICU, Fondazione IRCCS Cà Granda Ospedale Maggiore Policlinico, Milan, Italy; Emiliana Calappi, Neuro ICU, Fondazione IRCCS Cà Granda Ospedale Maggiore Policlinico, Milan, Italy; Maria Rosa Calvi, Department of Anesthesiology and Intensive Care, S Raffaele University Hospital, Milan, Italy; Peter Cameron, ANZIC Research Center, Monash University, Department of Epidemiology and Preventive Medicine, Melbourne, Victoria, Australia; Guillermo

Carbayo Lozano, Department of Neurosurgery, Hospital of Cruces, Bilbao, Spain; Marco Carbonara, Neuro ICU, Fondazione IRCCS Cà Granda Ospedale Maggiore Policlinico, Milan, Italy; Giorgio Chevallard, NeuroIntensive Care, Niguarda Hospital, Milan, Italy; Arturo Chieregato, NeuroIntensive Care, Niguarda Hospital, Milan, Italy; Giuseppe Citerio, School of Medicine and Surgery, Università Milano Bicocca, Milano, Italy, and NeuroIntensive Care, ASST di Monza, Monza, Italy; Maryse Cnossen, Department of Public Health, Erasmus Medical Center-University Medical Center, Rotterdam, the Netherlands; Mark Coburn, Department of Anesthesiology, University Hospital of Aachen, Aachen, Germany; Jonathan Coles, Department of Anesthesia and Neurointensive Care, Cambridge University Hospital NHS Foundation Trust, Cambridge, United Kingdom; Jamie D. Cooper, School of Public Health and PM, Monash University and the Alfred Hospital, Melbourne, Victoria, Australia; Marta Correia, Radiology/MRI Department, MRC Cognition and Brain Sciences Unit, Cambridge, United Kingdom; Amra Čović, Institute of Medical Psychology and Medical Sociology, Universitätsmedizin Göttingen, Göttingen, Germany; Nicola Curry, Oxford University Hospitals NHS Trust, Oxford, United Kingdom; Endre Czeiter, Department of Neurosurgery, Medical School, University of Pécs, Hungary and Neurotrauma Research Group, János Szentágothai Research Center, University of Pécs, Hungary; Marek Czosnyka, Brain Physics Lab, Division of Neurosurgery, Department of Clinical Neurosciences, University of Cambridge, Addenbrooke's Hospital, Cambridge, United Kingdom; Claire Dahyot Fizelier, Intensive Care Unit, CHU Poitiers, Potiers, France; Helen Dawes, Movement Science Group, Faculty of Health and Life Sciences, Oxford Brookes University, Oxford, United Kingdom; Véronique De Keyser, Department of Neurosurgery, Antwerp University Hospital and University of Antwerp, Edegem, Belgium; Vincent Degos, Anesthesie-Réanimation, Assistance Publique—Hopitaux de Paris, Paris, France; Francesco Della Corte, Department of Anesthesia and Intensive Care, Maggiore Della Carità Hospital, Novara, Italy; Hugo den Boogert, Department of Neurosurgery, Radboud University Medical Center, Nijmegen, the Netherlands; Bart Depreitere, Department of Neurosurgery, University Hospitals Leuven, Leuven, Belgium; Đula Đilvesi, Department of Neurosurgery, Clinical Center of Vojvodina, Faculty of Medicine, University of Novi Sad, Novi Sad, Serbia; Abhishek Dixit, Division of Anesthesia, University of Cambridge, Addenbrooke's Hospital, Cambridge, United Kingdom; Emma Donoghue, Australian and New Zealand Intensive Care Research Center, Department of Epidemiology and Preventive Medicine, School of Public Health and Preventive Medicine, Monash University, Melbourne, Australia; Jens Dreier, Center for Stroke Research Berlin, Charité—Universitätsmedizin Berlin, corporate member of Freie Universität Berlin, Humboldt-Universität zu Berlin, and Berlin Institute of Health, Berlin, Germany; Guy Loup Dulière, Intensive Care Unit, CHR Citadelle, Liège, Belgium; Ari Ercole, Division of Anesthesia, University of Cambridge, Addenbrooke's Hospital, Cambridge, United Kingdom; Patrick Esser, Movement Science Group, Faculty of Health and Life Sciences, Oxford Brookes University, Oxford, United Kingdom; Erzsébet Ezer, Department of Anesthesiology and Intensive Therapy, University of Pécs, Pécs, Hungary; Martin Fabricius, Departments of Neurology, Clinical Neurophysiology and Neuroanesthesiology, Region Hovedstaden Rigshospitalet, Copenhagen, Denmark; Valery L. Feigin, National Institute for Stroke and Applied Neurosciences, Faculty of Health and Environmental Studies, Auckland University of Technology, Auckland, New Zealand; Kelly Foks, Department of Neurology, Erasmus MC, Rotterdam, the Netherlands; Shirin Frisvold, Department of Anesthesiology and Intensive Care, University Hospital Northern Norway, Tromso, Norway; Alex Furmanov, Department of Neurosurgery, Hadassah-Hebrew University Medical center, Jerusalem, Israel; Pablo Gagliardo, Fundación Instituto Valenciano de Neurorrehabilitación (FIVAN), Valencia, Spain; Damien Galanaud, Anesthesie-Réanimation, Assistance Publique—Hopitaux de Paris, Paris, France; Dashiell Gantner, ANZIC Research Center, Monash University, Department of Epidemiology and Preventive Medicine, Melbourne, Australia; Guoyi Gao, Department of Neurosurgery, Shanghai Renji Hospital, Shanghai Jiaotong University/School of Medicine, Shanghai, China; Pradeep George, Karolinska Institutet, INCF International Neuroinformatics Coordinating Facility, Stockholm, Sweden; Alexandre Ghuysen, Emergency Department, CHU, Liège, Belgium; Lelde Giga, Neurosurgery Clinic, Pauls Stradins Clinical University Hospital, Riga, Latvia; Ben Glocker, Department of Computing, Imperial College London, London, United Kingdom; Jagoš Golubovic, Department of Neurosurgery, Clinical Center of Vojvodina, Faculty of Medicine, University of Novi Sad, Novi Sad, Serbia; Pedro A. Gomez, Department of Neurosurgery, Hospital Universitario 12 de Octubre, Madrid, Spain; Johannes Gratz, Department of Anesthesia, Critical Care and Pain Medicine, Medical University of Vienna, Austria; Benjamin Gravesteijn, Department of Public Health, Erasmus Medical Center-University Medical Center, Rotterdam, the Netherlands; Francesca Grossi, Department of Anesthesia and Intensive Care, Maggiore Della Carità Hospital, Novara, Italy; Russell L. Gruen, College of Health and Medicine, Australian National University, Canberra, Australia; Deepak Gupta, Department of Neurosurgery, Neurosciences Center and JPN Apex Trauma Center, All India Institute of Medical Sciences, New Delhi, India; Juanita A. Haagsma, Department of Public Health, Erasmus Medical Center-University Medical Center, Rotterdam, the Netherlands; Iain Haitsma, Department of Neurosurgery, Erasmus MC, Rotterdam, the Netherlands; Raimund Helbok, Department of Neurology, Neurological Intensive Care Unit, Medical University of Innsbruck, Innsbruck, Austria; Eirik Helseth, Department of Neurosurgery, Oslo University Hospital, Oslo, Norway; Lindsay Horton, Division of Psychology, University of Stirling, Stirling, United Kingdom; Jilske Huijben, Department of Public Health, Erasmus Medical Center-University Medical Center, Rotterdam, the Netherlands; Peter J. Hutchinson, Division of Neurosurgery, Department of Clinical Neurosciences, Addenbrooke's Hospital and University of Cambridge, Cambridge, United Kingdom; Bram Jacobs, Department of Neurology, University of Groningen, University Medical Center Groningen, Groningen, the Netherlands; Stefan Jankowski, Neurointensive Care, Sheffield Teaching Hospitals NHS Foundation Trust, Sheffield, United Kingdom; Mike Jarrett, Quesgen Systems Inc., Burlingame, California; Ji yao Jiang, Department of Neurosurgery, Shanghai Renji hospital, Shanghai Jiaotong University/School of Medicine, Shanghai, China; Kelly Jones, National Institute for Stroke and Applied Neurosciences, Faculty of Health and Environmental Studies, Auckland University of Technology, Auckland, New Zealand; Mladen Karan, Center for Stroke Research Berlin, Charité—Universitätsmedizin Berlin, Corporate Member of Freie Universität Berlin, Humboldt-Universität zu Berlin, and Berlin Institute of Health, Berlin, Germany; Angelos G. Kolias, Division of Neurosurgery, Department of Clinical Neurosciences, Addenbrooke's Hospital and University of Cambridge, Cambridge, United Kingdom; Erwin Kompanje, Department of Intensive Care and Department of Ethics and Philosophy of Medicine, Erasmus Medical Center, Rotterdam, the Netherlands; Daniel

Kondziella, Departments of Neurology, Clinical Neurophysiology, and Neuroanesthesiology, Region Hovedstaden Rigshospitalet, Copenhagen, Denmark; Evgenios Koraropoulos, Division of Anesthesia, University of Cambridge, Addenbrooke's Hospital, Cambridge, United Kingdom; Lars Owe Koskinen, Department of Clinical Neuroscience, Neurosurgery, Umeå University, Umeå, Sweden; Noémi Kovács, Hungarian Brain Research Program—Grant No. KTIA_13_NAP-A-II/8, University of Pécs, Pécs, Hungary; Alfonso Lagares, Department of Neurosurgery, Hospital Universitario 12 de Octubre, Madrid, Spain; Linda Lanyon, Karolinska Institutet, INCF International Neuroinformatics Coordinating Facility, Stockholm, Sweden; Steven Laureys, Cyclotron Research Center, University of Liège, Liège, Belgium; Fiona Lecky, Emergency Medicine Research in Sheffield, Health Services Research Section, School of Health and Related Research (ScHARR), University of Sheffield, Sheffield, United Kingdom; Rolf Lefering, Institute of Research in Operative Medicine (IFOM), Witten/Herdecke University, Cologne, Germany; Valerie Legrand, VP Global Project Management CNS, ICON, Paris, France; Aurelie Lejeune, Department of Anesthesiology-Intensive Care, Lille University Hospital, Lille, France; Leon Levi, Department of Neurosurgery, Rambam Medical Center, Haifa, Israel; Roger Lightfoot, Department of Anesthesiology and Intensive Care, University Hospital Southhampton NHS Trust, Southhampton, United Kingdom; Hester Lingsma, Department of Public Health, Erasmus Medical Center-University Medical Center, Rotterdam, the Netherlands; Ana M. Castaño León, Department of Neurosurgery, Hospital Universitario 12 de Octubre, Madrid, Spain; Marc Maegele, Cologne-Merheim Medical Center (CMMC), Department of Traumatology, Orthopedic Surgery and Sportmedicine, Witten/Herdecke University, Cologne, Germany; Marek Majdan, Department of Public Health, Faculty of Health Sciences and Social Work, Trnava University, Trnava, Slovakia; Alex Manara, Intensive Care Unit, Southmead Hospital, Bristol, Bristol, United Kingdom; Geoffrey Manley, Department of Neurological Surgery, University of California, San Francisco, California; Costanza Martino, Department of Anesthesia and Intensive Care, M. Bufalini Hospital, Cesena, Italy; Hugues Maréchal, Intensive Care Unit, CHR Citadelle, Liège, Belgium; Julia Mattern, Department of Neurosurgery, University Hospital Heidelberg, Heidelberg, Germany; Catherine McMahon, Department of Neurosurgery, the Walton Center NHS Foundation Trust, Liverpool, United Kingdom; Béla Melegh, Department of Medical Genetics, University of Pécs, Pécs, Hungary; David Menon, Division of Anesthesia, University of Cambridge, Addenbrooke's Hospital, Cambridge, United Kingdom; Tomas Menovsky, Department of Neurosurgery, Antwerp University Hospital and University of Antwerp, Edegem, Belgium; Davide Mulazzi, Neuro ICU, Fondazione IRCCS Cà Granda Ospedale Maggiore Policlinico, Milan, Italy; Visakh Muraleedharan, Karolinska Institutet, INCF International Neuroinformatics Coordinating Facility, Stockholm, Sweden; Lynnette Murray, ANZIC Research Center, Monash University, Department of Epidemiology and Preventive Medicine, Melbourne, Australia; Nandesh Nair, Department of Neurosurgery, Antwerp University Hospital and University of Antwerp, Edegem, BelgiumAncuta Negru, Department of Neurosurgery, Emergency County Hospital Timisoara, Timisoara, Romania; David Nelson, Department of Physiology and Pharmacology, Section of Perioperative Medicine and Intensive Care, Karolinska Institutet, Stockholm, Sweden; Virginia Newcombe, Division of Anesthesia, University of Cambridge, Addenbrooke's Hospital, Cambridge, United Kingdom; Quentin Noirhomme, Cyclotron Research Center, University of Liège, Liège, Belgium; József Nyirádi, János Szentágothai Research Center, University of Pécs, Pécs, Hungary; Otesile Olubukola, Emergency Medicine Research in Sheffield, Health Services Research Section, School of Health and Related Research (ScHARR), University of Sheffield, Sheffield, United Kingdom; Matej Oresic, School of Medical Sciences, Örebro University, Örebro, Sweden; Fabrizio Ortolano, Neuro ICU, Fondazione IRCCS Cà Granda Ospedale Maggiore Policlinico, Milan, Italy; Aarno Palotie, Institute for Molecular Medicine Finland, University of Helsinki, Helsinki, Finland, Analytic and Translational Genetics Unit, Department of Medicine, Psychiatric and Neurodevelopmental Genetics Unit, Department of Psychiatry, and Department of Neurology, Massachusetts General Hospital, Boston, Massachusetts, Program in Medical and Population Genetics and the Stanley Center for Psychiatric Research, Broad Institute of MIT and Harvard, Cambridge, Massachusetts; Jean François Payen, Department of Anesthesiology and Intensive Care, University Hospital of Grenoble, Grenoble, France; Natascha Perera, International Projects Management, ARTTIC, Munchen, Germany, Vincent Perlbarg, Anesthesie-Réanimation, Assistance Publique—Hopitaux de Paris, Paris, France; Paolo Persona, Department of Anesthesia and Intensive Care, Azienda Ospedaliera Università di Padova, Padova, Italy; Wilco Peul, Department of Neurosurgery, Leiden University Medical Center, Leiden, the Netherlands and Department of Neurosurgery, Medical Center Haaglanden, the Hague, the Netherlands; Anna Piippo-Karjalainen, Department of Neurosurgery, Helsinki University Central Hospital, Helsinki, Finland; Matti Pirinen, Institute for Molecular Medicine Finland, University of Helsinki, Helsinki, Finland; Horia Ples, Department of Neurosurgery, Emergency County Hospital Timisoara, Timisoara, Romania; Suzanne Polinder, Department of Public Health, Erasmus Medical Center-University Medical Center, Rotterdam, the Netherlands; Inigo Pomposo, Department of Neurosurgery, Hospital of Cruces, Bilbao, Spain; Jussi P. Posti, Division of Clinical Neurosciences, Department of Neurosurgery and Turku Brain Injury Center, Turku University Hospital and University of Turku, Turku, Finland; Louis Puybasset, Department of Anesthesiology and Critical Care, Pitié -Salpêtrière Teaching Hospital, Assistance Publique, Hôpitaux de Paris and University Pierre et Marie Curie, Paris, France; Andreea Radoi, Neurotraumatology and Neurosurgery Research Unit (UNINN), Vall d'Hebron Research Institute, Barcelona, Spain; Arminas Ragauskas, Department of Neurosurgery, Kaunas University of Technology and Vilnius University, Vilnius, Lithuania; Rahul Raj, Department of Neurosurgery, Helsinki University Central Hospital, Helsinki, Finland; Malinka Rambadagalla, Department of Neurosurgery, Rezekne Hospital, Latvia; Ruben Real, Institute of Medical Psychology and Medical Sociology, Universitätsmedizin Göttingen, Göttingen, Germany; Jonathan Rhodes, Department of Anesthesia, Critical Care and Pain Medicine NHS Lothian and University of Edinburg, Edinburgh, United Kingdom; Sylvia Richardson, MRC Biostatistics Unit, Cambridge Institute of Public Health, Cambridge, United Kingdom; Sophie Richter, Division of Anesthesia, University of Cambridge, Addenbrooke's Hospital, Cambridge, United Kingdom; Samuli Ripatti, Institute for Molecular Medicine Finland, University of Helsinki, Helsinki, Finland; Saulius Rocka, Department of Neurosurgery, Kaunas University of Technology and Vilnius University, Vilnius, Lithuania; Cecilie Roe, Department of Physical Medicine and Rehabilitation, Oslo University Hospital/University of Oslo, Oslo, Norway; Olav Roise, Division of Surgery and Clinical Neuroscience, Oslo University Hospital, Oslo, Norway; Jonathan Rosand, Broad Institute, Cambridge, Massachusetts, Harvard Medical School, Boston, Massachusetts, Massachusetts General Hospital, Boston, Massachusetts; Jeffrey V. Rosenfeld, National Trauma Research Institute, the Alfred Hospital, Monash University, Melbourne,

Australia; Christina Rosenlund, Department of Neurosurgery, Odense University Hospital, Odense, Denmark; Guy Rosenthal, Department of Neurosurgery, Hadassah-Hebrew University Medical center, Jerusalem, Israel; Rolf Rossaint, Department of Anesthesiology, University Hospital of Aachen, Aachen, Germany; Sandra Rossi, Department of Anesthesia and Intensive Care, Azienda Ospedaliera Università di Padova, Padova, Italy; Daniel Rueckert, Department of Computing, Imperial College London, London, United Kingdom; Martin Rusnák, International Neurotrauma Research Organisation, Vienna, Austria; Juan Sahuquillo, Neurotraumatology and Neurosurgery Research Unit (UNINN), Vall d'Hebron Research Institute, Barcelona, Spain; Oliver Sakowitz, Department of Neurosurgery, University Hospital Heidelberg, Heidelberg, Germany, Klinik für Neurochirurgie, Klinikum Ludwigsburg, Ludwigsburg, Germany; Renan Sanchez Porras, Klinik für Neurochirurgie, Klinikum Ludwigsburg, Ludwigsburg, Germany; Janos Sandor, Division of Biostatistics and Epidemiology, Department of Preventive Medicine, University of Debrecen, Debrecen, Hungary; Nadine Schäfer, Institute of Research in Operative Medicine (IFOM), Witten/Herdecke University, Cologne, Germany; Silke Schmidt, Department Health and Prevention, University Greifswald, Greifswald, Germany; Herbert Schoechl, Department of Anaesthesiology and Intensive Care, AUVA Trauma Hospital, Salzburg, Austria; Guus Schoonman, Department of Neurology, Elisabeth-TweeSteden Ziekenhuis, Tilburg, the Netherlands; Rico Frederik Schou, Department of Neuroanesthesia and Neurointensive Care, Odense University Hospital, Odense, Denmark, Elisabeth Schwendenwein, Trauma Surgery, Medical University Vienna, Vienna, Austria; Charlie Sewalt, Department of Public Health, Erasmus Medical Center-University Medical Center, Rotterdam, the Netherlands; Toril Skandsen, Department of Neuromedicine and Movement Science, Norwegian University of Science and Technology, NTNU, Trondheim, Norway, Department of Physical Medicine and Rehabilitation, St. Olavs Hospital, Trondheim University Hospital, Trondheim, Norway; Peter Smielewski, Brain Physics Lab, Division of Neurosurgery, Department of Clinical Neurosciences, University of Cambridge, Addenbrooke's Hospital, Cambridge, United Kingdom; Abayomi Sorinola, Department of Neurosurgery, University of Pécs, Pécs, Hungary; Emmanuel Stamatakis, Division of Anesthesia, University of Cambridge, Addenbrooke's Hospital, Cambridge, United Kingdom; Simon Stanworth, Oxford University Hospitals NHS Trust, Oxford, United Kingdom; Ana Stevanovic, Department of Anesthesiology, University Hospital of Aachen, Aachen, Germany; Robert Stevens, Division of Neuroscience Critical Care, John Hopkins University School of Medicine, Baltimore, Maryland; William Stewart, Department of Neuropathology, Queen Elizabeth University Hospital and University of Glasgow, Glasgow, United Kingdom; Ewout W. Steyerberg, Department of Public Health, Erasmus Medical Center-University Medical Center, Rotterdam, the Netherlands and Department of Biomedical Data Sciences, Leiden University Medical Center, Leiden, the Netherlands; Nino Stocchetti, Department of Pathophysiology and Transplantation, Milan University, and Neuroscience ICU, Fondazione IRCCS Cà Granda Ospedale Maggiore Policlinico, Milano, Italy; Nina Sundström, Department of Radiation Sciences, Biomedical Engineering, Umeå University, Umeå, Sweden; Anneliese Synnot, Australian and New Zealand Intensive Care Research Center, Department of Epidemiology and Preventive Medicine, School of Public Health and Preventive Medicine, Monash University, Melbourne, Australia, and Cochrane Consumers and Communication Review Group, Center for Health Communication and Participation, School of Psychology and Public Health, La Trobe University, Melbourne, Australia; Riikka Takala, Perioperative Services, Intensive Care Medicine and Pain Management, Turku University Hospital and University of Turku, Turku, Finland; Viktória Tamás, Department of Neurosurgery, University of Pécs, Pécs, Hungary; Tomas Tamosuitis, Department of Neurosurgery, Kaunas University of Health Sciences, Kaunas, Lithuania; Mark Steven Taylor, Department of Public Health, Faculty of Health Sciences and Social Work, Trnava University, Trnava, Slovakia; Braden Te Ao, National Institute for Stroke and Applied Neurosciences, Faculty of Health and Environmental Studies, Auckland University of Technology, Auckland, New Zealand; Olli Tenovuo, Division of Clinical Neurosciences, Department of Neurosurgery and Turku Brain Injury Center, Turku University Hospital and University of Turku, Turku, Finland; Alice Theadom, National Institute for Stroke and Applied Neurosciences, Faculty of Health and Environmental Studies, Auckland University of Technology, Auckland, New Zealand; Matt Thomas, Intensive Care Unit, Southmead Hospital, Bristol, Bristol, United Kingdom; Dick Tibboel, Intensive Care and Department of Pediatric Surgery, Erasmus Medical Center, Sophia Children's Hospital, Rotterdam, the Netherlands; Marjolein Timmers, Department of Intensive Care and Department of Ethics and Philosophy of Medicine, Erasmus Medical Center, Rotterdam, the Netherlands; Christos Tolias, Department of Neurosurgery, Kings college London, London, United Kingdom; Tony Trapani, ANZIC Research Center, Monash University, Department of Epidemiology and Preventive Medicine, Melbourne, Victoria, Australia; Cristina Maria Tudora, Department of Neurosurgery, Emergency County Hospital Timisoara, Timisoara, Romania; Peter Vajkoczy, Neurologie, Neurochirurgie und Psychiatrie, Charité—Universitätsmedizin Berlin, Berlin, Germany; Shirley Vallance, ANZIC Research Center, Monash University, Department of Epidemiology and Preventive Medicine, Melbourne, Victoria, Australia; Egils Valeinis, Neurosurgery Clinic, Pauls Stradins Clinical University Hospital, Riga, Latvia; Zoltán Vámos, Department of Anesthesiology and Intensive Therapy, University of Pécs, Pécs, Hungary; Gregory Van der Steen, Department of Neurosurgery, Antwerp University Hospital and University of Antwerp, Edegem, Belgium; Joukje van der Naalt, Department of Neurology, University of Groningen, University Medical Center Groningen, Groningen, the Netherlands; Jeroen T.J.M. van Dijck, Department of Neurosurgery, Leiden University Medical Center, Leiden, the Netherlands and Department of Neurosurgery, Medical Center Haaglanden, the Hague, the Netherlands; Thomas A. van Essen, Department of Neurosurgery, Leiden University Medical Center, Leiden, the Netherlands and Department of Neurosurgery, Medical Center Haaglanden, the Hague, the Netherlands; Wim Van Hecke, icoMetrix NV, Leuven, Belgium; Caroline van Heugten, Movement Science Group, Faculty of Health and Life Sciences, Oxford Brookes University, Oxford, United Kingdom; Dominique Van Praag, Psychology Department, Antwerp University Hospital, Edegem, Belgium; Audrey Vanhaudenhuyse, Anesthesie-Réanimation, Assistance Publique—Hopitaux de Paris, Paris, France, and Cyclotron Research Center, University of Liège, Liège, Belgium; Roel P. J. van Wijk, Department of Neurosurgery, Helsinki University Central Hospital, Helsinki, Finland; Alessia Vargiolu, NeuroIntensive Care, ASST di Monza, Monza, Italy; Emmanuel Vega, Department of Neurosurgery, Rambam Medical Center, Haifa, Israel; Kimberley Velt, Department of Public Health, Erasmus Medical Center-University Medical Center, Rotterdam, the Netherlands; Paul M. Vespa, Director of Neurocritical Care, University of California, Los Angeles, California; Anne Vik, Department of Neuromedicine and Movement Science, Norwegian University of Science and Technology, NTNU, Trondheim, Norway, and Department of

Neurosurgery, St.Olavs Hospital, Trondheim University Hospital, Trondheim, Norway; Rimantas Vilcinis, Department of Neurosurgery, Kaunas University of Health Sciences, Kaunas, Lithuania; Victor Volovici, Department of Neurosurgery, Erasmus MC, Rotterdam, the Netherlands; Nicole von Steinbüchel, Institute of Medical Psychology and Medical Sociology, Universitätsmedizin Göttingen, Göttingen, Germany; Daphne Voormolen, Department of Public Health, Erasmus Medical Center-University Medical Center, Rotterdam, the Netherlands; Petar Vulekovic, Department of Neurosurgery, Clinical Center of Vojvodina, Faculty of Medicine, University of Novi Sad, Novi Sad, Serbia; Kevin K.W. Wang, Department of Emergency Medicine, University of Florida, Gainesville, Florida; Eveline Wiegers, Department of Public Health, Erasmus Medical Center-University Medical Center, Rotterdam, the Netherlands; Guy Williams, Division of Anesthesia, University of Cambridge, Addenbrooke's Hospital, Cambridge, United Kingdom; Lindsay Wilson, Division of Psychology, University of Stirling, Stirling, United Kingdom; Stefan Winzeck, Division of Anesthesia, University of Cambridge, Addenbrooke's Hospital, Cambridge, United Kingdom; Stefan Wolf, Department of Neurosurgery, Charité—Universitätsmedizin Berlin, corporate member of Freie Universität Berlin, Humboldt-Universität zu Berlin, and Berlin Institute of Health, Berlin, Germany; Zhihui Yang, Department of Emergency Medicine, University of Florida, Gainesville, Florida; Peter Ylén, VTT Technical Research Center, Tampere, Finland; Alexander Younsi, Department of Neurosurgery, University Hospital Heidelberg, Heidelberg, Germany; Frederik A. Zeiler, Division of Anesthesia, University of Cambridge, Addenbrooke's Hospital, Cambridge, United Kingdom, and Section of Neurosurgery, Department of Surgery, Rady Faculty of Health Sciences, University of Manitoba, Winnipeg, Manitoba Veronika Zelinkova, Department of Public Health, Faculty of Health Sciences and Social Work, Trnava University, Trnava, Slovakia; Agate Ziverte, Neurosurgery Clinic, Pauls Stradins Clinical University Hospital, Riga, Latvia; Tommaso Zoerle, Neuro ICU, Fondazione IRCCS Cà Granda Ospedale Maggiore Policlinico, Milan, Italy.

Acknowledgments

Data used in preparation of this manuscript were obtained in the context of CENTER-TBI, a large collaborative project with the support of the European Commission 7th Framework program (602150).

Funding Information

Funding of additional elements has been provided by the Hannelore Kohl

Foundation (Germany) and by the non-profit organization One Mind.

Author Disclosure Statement

No competing financial interests exist.

Supplementary Material

Supplementary Table S1
Supplementary Table S2
Supplementary Table S3
Supplementary Table S4

References

1. Parizel, P.M., Van Goethem, J.W., Özsarlak, O., Maes, M., and Phillips, C.D. (2005). New developments in the neuroradiological diagnosis of craniocerebral trauma. Eur. Radiol. 15, 569–581.
2. Haacke, E.M., Duhaime, C., Gean, A.D., Riedy, G., Wintermark, M., Mukherjee, P., Brody, D.L., Degraba, T., Duncan, T.D., Elovic, E., Hurley, R., Latour, L., Smirniotopoulos, J.G., and Smith, D.H. (2010). Common Data Elements in radiologic imaging of traumatic brain injury. J. Magn. Reson. Imaging. 543, 516–543.
3. Huff, J.S. and Jahar, S. (2014). Differences in interpretation of cranial computed tomography in ED traumatic brain injury patients by expert neuroradiologists. Am. J. Emerg. Med. 32, 606–608.
4. Laalo, J.P., Kurki, T.J., Sonninen, P.H., and Tenovuo, O.S. (2009). Reliability of diagnosis of traumatic brain injury by computed tomography in the acute phase. J. Neurotrauma 26, 2169–2178.
5. Maas, A.I.R., Harrison-Felix, C.L., Menon, D., Adelson, P.D., Balkin, T., Bullock, R., Engel, D.C., Gordon, W., Langlois-Orman, J., Lew, H.L., Robertson, C., Temkin, N., Valadka, A., Verfaellie, M., Wainwright, M., Wright, D.W., and Schwab, K. (2011). Standardizing data collection in traumatic brain injury. J. Neurotrauma 28, 177–187.
6. Duhaime, A.C., Gean, A.D., Haacke, E.M., Hicks, R., Wintermark, M., Mukherjee, P., Brody, D., Latour, L., and Riedy, G. (2010). Common data elements in radiologic imaging of traumatic brain injury. Arch. Phys. Med. Rehabil. 91, 1661–1666.
7. Yue, J.K. Vassar, M.J., Lingsma, H.F., Cooper, S.R., Okonkwo, D.O., Valadka, A.B., Gordon, W.A., Maas, A.I., Mukherjee, P., Yuh, E.L., Puccio, A.M., Schnyer, D.M., and Manley, G.T.; TRACK-TBI Investigators. (2013). Transforming Research and Clinical Knowledge in Traumatic Brain Injury Pilot: multicenter implementation of the Common Data Elements for traumatic brain injury. J. Neurotrauma 30, 1831–1844.
8. Maas, A.I.R., Menon, D.K., Steyerberg, E.W., Citerio, G., Lecky, F., Manley, G.T., Hill, S., Legrand, V., and Sorgner, A. (2015). Collaborative European NeuroTrauma Effectiveness Research in Traumatic Brain Injury (CENTER-TBI). Neurosurgery 76, 67–80.
9. Harburg, L., Mccormack, E., Kenney, K., Moore, C., Yang, K., Vos, P., Jacobs, B., Madden, C.J., Diaz-arrastia, R., Harburg, L., Mccormack, E., Kenney, K., Moore, C., Yang, K., Vos, P., Jacobs, B., Madden, C.J., Diaz-arrastia, R., and Bogoslovsky, T. (2017). Reliability of the NINDS common data elements cranial tomography (CT) rating variables for traumatic brain injury (TBI) variables for traumatic brain injury (TBI). Brain Inj. 31, 174–184.
10. Vande Vyvere, T., Wilms, G., Claes, L., Martin Leon, F., Nieboer, D., Verheyden, J., van den Hauwe, L., Pullens, P., Maas, A.I.R., and Parizel, P.M. (2019). Central versus local radiological reading of acute computed tomography characteristics in multi-center traumatic brain injury Research. J. Neurotrauma 36, 1080–1092.
11. Bullock, R.M. (2006). Appendix II: evaluation of relevant computed tomographic scan findings. Neurosurgery 58, 1.
12. Webb, A.J., Ullman, N.L., Morgan, T.C., Muschelli, J., Kornbluth, J., Awad, I.A., Mayo, S., Rosenblum, M., Ziai, W., Zuccarrello, M., Aldrich, F., John, S., Harnof, S., Lopez, G., Broaddus, W.C., Wijman, C., Vespa, P., Bullock, R., Haines, S.J., Cruz-Flores, S., Tuhrim, S., Hill, M.D., Narayan, R., and Hanley, D.F.; MISTIE and CLEAR Investigators. (2015). Accuracy of the ABC/2 score for intracerebral hemorrhage: systematic review and analysis of MISTIE, CLEAR-IVH, and CLEAR III. Stroke 46, 2470–2476.
13. Alali, A.S., Vavrek, D., Barber, J., Dikmen, S., Nathens, A.B., and Temkin, N.R. (2015). Comparative study of outcome measures and analysis methods for traumatic brain injury trials. J. Neurotrauma 32, 581–589.
14. Hossain, I., Mohammadian, M., Takala, R.S.K., Tenovuo, O., Lagerstedt, L., Ala-Seppala, H., Frantzen, J., van Gils, M., Hutchinson, P., Katila, A.J., Maanpaa, H.-R., Menon, D.K., Newcombe, V.F., Tallus, J., Hrusovsky, K., Wilson, D.H., Blennow, K., Sanchez, J.-C., Zetterberg, H., and Posti, J.P. (2019). Early levels of glial fibrillary acidic protein and neurofilament light protein in predicting the outcome of mild traumatic brain injury. J. Neurotrauma 36, 1551–1560.
15. Gelman, A. (2008). Scaling regression inputs by dividing by two standard deviations. Stat. Med. 27, 2865–2873.
16. Tibshirani, R. (2011). Regression shrinkage and selection via the lasso: a retrospective. J. R. Stat. Soc. Series B 73, 273–282.
17. Zou, H. and Hastie, T. (2005). Regularization and variable selection via the elastic net. J. R. Stat. Soc. 301–320.

18. Steyerberg, E.W., Bleeker, S.E., Moll, H.A., Grobbee, D.E., and Moons, K.G.M. (2003). Internal and external validation of predictive models: a simulation study of bias and precision in small samples. J. Clin. Epidemiol. 56, 441–447.
19. Maas, A.I.R., Hukkelhoven, C.W.P.M., Marshall, L.F., and Steyerberg, E.W. (2005). Prediction of outcome in traumatic brain injury with computed tomographic characteristics: A comparison between the computed tomographic classification and combinations of computed tomographic predictors. Neurosurgery 57, 1173–1181.
20. Thelin, E.P., Nelson, D.W., Vehviläinen, J., Nyström, H., Kivisaari, R., Siironen, J., Svensson, M., Skrifvars, M.B., Bellander, B.M., and Raj, R. (2017). Evaluation of novel computerized tomography scoring systems in human traumatic brain injury: an observational, multicenter study. PLoS Med. 14.
21. Hu, Y., Sun, H., Yuan, Y., Li, Q., Huang, S., Jiang, S., Liu, K., and Yang, C. (2015). Acute bilateral mass-occupying lesions in non-penetrating traumatic brain injury: a retrospective study. BMC Surg. 15, 6.
22. Clarençon, F., Bardinet, É., Martinerie, J., Pelbarg, V., Menjot de Champfleur, N., Gupta, R., Tollard, E., Soto-Ares, G., Ibarrola, D., Schmitt, E., Tourdias, T., Degos, V., Yelnik, J., Dormont, D., Puybasset, L., and Galanaud, D.; Neuro Imaging for Coma Emergence and Recovery (NICER) Consortium. (2017). Lesions in deep gray nuclei after severe traumatic brain injury predict neurologic outcome. PLOS One 12.
23. Lawrence F. Marshall, Sharon Bowers Marshall, Melville R. Klauber, Marjan van Berkum Clark, Howard M. Eisenberg, John A. Jane, Thomas G. Luerssen, Anthony Marmarou, and Mary A. Foulkes. (1991). A new classification of head injury based on computerized tomography. J. Neurosurg. 75, S14–S20.
24. Wintermark, M., Li, Y., Ding, V.Y., Xu, Y., Jiang, B., Ball, R.L., Zeineh, M., Gean, A., and Sanelli, P. (2018). NeuroImaging radiological interpretation system for acute traumatic brain injury (TBI). J. Neurotrauma 35, 2665–2672.
25. Rubin, D.L. and Kahn, C.E. (2017). Common Data Elements in radiology. Radiology 283, 837–844.
26. Barras, C.D., Asadi, H., Phal, P.M., Tress, B.M., Davis, S.M., Patricia, M., and Desmond, P.M. (2016). Audit of CT reporting standards in cases of intracerebral haemorrhage at a comprehensive stroke centre in Australia. J. Med. Imaging Radiat. Oncol. 60, 720–727.
27. Bullock, M.R., Chesnut, R., Ghajar, J., Gordon, D., Hartl, R., Newell, D.W., Servadei, F., Walters, B.C., and Wilberger, J.E. (2006). Neurosurgery S21–S23.
28. Jain, S., Vyvere, T. Vande, Terzopoulos, V., Sima, D.M., Roura, E., Maas, A., Wilms, G., and Verheyden, J. (2019). Automatic quantification of computed tomography features in acute traumatic brain injury. J. Neurotrauma 10, 1–10.
29. Yuh, E.L., Cooper, S.R., Ferguson, A.R., and Manley, G.T. (2012). Quantitative CT improves outcome prediction in acute traumatic brain injury. J. Neurotrauma 746, 735–746.
30. McHugh, G.S., Butcher, I., Steyerberg, E.W., Marmarou, A., Lu, J., Lingsma, H.F., Weir, J., Maas, A.I.R., and Murray, G.D. (2010). A simulation study evaluating approaches to the analysis of ordinal outcome data in randomized controlled trials in traumatic brain injury: results from the IMPACT Project. Clinical Trials 7, 44–57.

Address correspondence to:
Thijs Vande Vyvere, MSc
Department of Radiology
Neuroradiology Division
Antwerp University Hospital and University of Antwerp
Wilrijkstraat 10, 2650
Antwerp
Belgium

E-mail: vandevyverethijs@gmail.com