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Through the looking glass: early non-invasive imaging in TBI predicts the need for interventions

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ABSTRACT

Background Early diagnosis and treatment of traumatic brain injury (TBI) lead to better outcomes. It is difficult to predict which patients benefit from specialised centres, leading to over triage or delay in definitive care. We propose that a non-invasive test comprising optic nerve sheath ultrasound, transcranial Doppler and quantitative papillary reactivity is feasible, correlates with CT findings and may allow for accurate early identification of TBI.

Methods A 1-year, prospective observation study evaluated a low-risk, non-invasive method of assessing brain injury. Patients underwent a non-invasive neurological examination for trauma, including the above assessments. Data from the three examinations were collected within 6 hours of injury and at 24 hours, and were analysed. Demographics, haemodynamic data, imaging results and short-term outcomes/interventions were recorded.

Results Trauma patients over the age of 18 years, with a Glasgow coma scale (GCS) of <12 or CT evidence of TBI, and intubated were included (N=100). These were divided into +CT (n=49) and −CT groups (n=51) according to the Marshall CT classification of TBI. The +CT group was older, with worse GCS and higher lactate (p=0.008, p=0.001 and p=0.01) but were otherwise well matched. The +CT group included all TBI types, with 96% of the patients having more than one type of TBI. Pulsatility index and neurologic pupillary index were predictive of a +CT (p=0.04, p=0.02). Area under the receiver-operating curve for the logistic regression model for the prediction of positive radiographic findings was r=0.718. Finally, we suggest a preliminary scoring heuristic for predicting a positive radiological finding in a patient with TBI.

Conclusions The proposed examination is a feasible, non-invasive tool that may have clinical utility in the early prediction of TBI. If validated, it may improve trauma triage for the brain-injured patient. Further studies are warranted to validate this model.

BACKGROUND

Traumatic brain injury (TBI) is a leading cause of death, disability and cost in the USA.[1] Prevention, early recognition and treatment of secondary insults to the brain improve outcomes.[2] [3] Recognition of this has led to a significant reduction in TBI mortality from 50% to <25% over the past three decades, even after adjusting for age, severity of injury and other prognostic parameters.[4] Outcomes are also dependent on hospital triage, with most literature supporting early triage to a trauma center.[5] [6]

Glasgow coma scale (GCS) and pupil reactivity are used as initial triage tools in trauma, but they are far from perfect. While intended to be reproducible and a 'common language' between providers, inter-rater reliability has been shown to be poor.[7] Variations in component scores may give the same total GCS but predict far different outcomes.[8] Accurate scoring is confounded by patient intoxication, compromised physiology, a chaotic trauma environment and provider training.[9]

Identification of an objective, reliable and non-invasive method for identifying brain injury would in theory allow for targeted triage and earlier interventions. We evaluated a point-of-care TBI screening test: a combination of rapid transcranial Doppler (TCD) at the middle cerebral artery (MCA), optic nerve sheath diameter (ONSD) ultrasound and quantitative pupillary reactivity (QPR) to narrow the triage gap. This tri-modal approach assesses blood flow with TCD, anatomic changes with ONSD and brainstem function with pupillometry. All components of this examination are well established and currently clinically available. Similar to focused assessment with sonography for trauma (FAST), application of this non-invasive technology can allow early assessment of disease and is especially desirable in the far-forward arena or when conventional imaging is not available.

We hypothesised that this non-invasive examination would accurately identify patients in need of neurosurgical interventions and correlate with early CT findings in suspected brain trauma. We also were interested in evaluating the feasibility of the examination in the setting of a busy trauma centre.

METHODS

With Institutional Review Board approval, a prospective observational study was performed at the R Adams Cowley Shock Trauma Center in Baltimore, Maryland, from July 2014 to June 2015. A total of 193 patients were screened; of them, 100 were enrolled (n=100). Inclusion criteria were age over 18 years, intubation in the field or within 1 hour of arrival, and the presence of a head CT. All examination components were non-invasive and considered minimal risk, and a 24-hour waiver of informed consent was granted. If a patient or representative declined consent or enrolment within 30 hours, they were removed from the study.

All patients underwent a non-invasive neurological examination within 6 hours of injury. Nearly all patients had the examination performed in the trauma bay, and 90% of them had the examination performed within the first hour of hospital arrival. A core group (four expert users JG, MV, CC and SM) performed the examination components. To reduce bias, all efforts were made to avoid interfering with the clinical care of the patients, no clinical decisions were based on the tested examination and testers were never part of the treatment team. Prehospital and hospital records were collected concurrently and reviewed. Demographic, haemodynamic, laboratory and imaging data were collected. The non-invasive examination was repeated at 24 hours (±6 hours) if consent was obtained.

Non-invasive neurological examination

The tested neurological examination has three components. Quantitative pupillometry was performed with a NeurOptics NPi-100 Pupillometer (Neuroptics, Irvine, California, USA), a hand-held device measuring pupillary light reflexes and pupil size. The eye is gently opened, a short video clip is obtained and an automated report is generated detailing pupil size as a maximum, minimum, per cent change and calculated 'neurological pupil index' (NPi). NPi is a proprietary calculation comparing variables such as pupil size, dilation and constriction velocity. A value is generated on a scale of 1–5. NPi <3 is abnormal. The examination takes 2–3 min.

Ultrasound examinations were performed on a Phillips CX 50 ultrasound system (Phillips Healthcare, Andover, Massachusetts, USA). ONSD was measured with a 7.5 MHz linear array transducer, using optic nerve presets. The transducer was placed over the closed eye and adjusted to obtain the best images of the nerve. Bilateral image clips were captured and stored, each eye was measured at least twice and an average ONSD was determined for each eye. The ONSD was measured 3 mm behind the orbit, according to the established standard, using simple calipers in the two-dimensional window. The examination was not performed if there was ocular trauma.

TCD data were collected using a 3.5 MHz phased array transducer and a specialised TCD software package. TCD ultrasonography was performed with a probe of 3.5 MHz due to poor penetration of signals at higher frequencies through the temporal acoustic window. Pulsed-wave Doppler was used to measure blood flow. Peak systolic velocity (PSV) and end-diastolic velocities (EDVs) were determined for the MCAs bilaterally. Short clips were taken of ~5–10 beats. The pulsatility index (PI) and resistive index (RI) were also calculated using automated software. All TCDs were performed through a transtemporal window.

Patients were required to have undergone a CT scan of the head as part of the inclusion criteria to allow for accurate comparison. All scans were performed on one of two dedicated trauma CT scanners (Philips Brilliance CT, Andover, MA 64 or 40 slice). All CT scan interpretations were performed by dedicated trauma radiologists, and the records were reviewed at the time of data analysis. Testers were blinded to the CT scan results at the time of the non-invasive neurologic testing.

Statistical analysis

Patients were divided into two groups based on CT findings: a brain injury group (CT positive for anatomic TBI, n=49) and a non-brain-injury group (those with a normal brain CT, n=51). To identify potential predictors for the model, univariate analyses were conducted for demographic, clinical, sonographic and additional diagnostic variables comparing groups. For categorical variables, comparisons were made using a χ^2 test or Fisher's exact test. For continuous variables, comparisons were made using t-test or the Kruskal-Wallis test for skewed variables.

All variables were considered for inclusion in a multivariable logistic regression model. Variables were selected with backwards selection using the Akaike information criterion (AIC) and the Bayesian information criterion (BIC). Variables were dropped either for being non-significant (p>0.10) or because of colinearity. Deselected variables were tested with the final model and re-introduced into the model if the p value was <0.05 to ensure that no significant predictors were removed.

Multivariable analysis was then used to derive a simple-to-use decision-making rule for identifying patients with a positive head CT using a minimal number of predictors. Based on the size of effect, four patient predictors were selected.[10][11] Each predictor represented a significant variable derived from the multivariable model. Regression coefficients were divided by the smallest coefficient and then rounded to the nearest integer, as described previously by Sullivan et al.[11] The sensitivity, specificity, negative predictive value and positive predictive value (PPV) for all possible cut-off values were calculated for the final integer-based score model. The final discriminatory ability of the prediction model was quantified using the area under the receiver-operating characteristic curve. Calibration was assessed using the Hosmer-Lemeshow χ^2 goodness-of-fit test.[12] The assumptions and fit of the logistic regression model were assessed using q–q plots, frequency histograms and goodness-of-fit tests.

Given the small sample, the internal bootstrap method described by Harrell et al,[13] a recommended approach to validation, was used[14] to reassign the variable weights for each sample. To test the validation of this method, the PPV was selected as the most meaningful measure of the rule's performance. PPV was calculated from the bootstrap iterations and applied to the resample. All statistical analyses were performed using Stata V.12.1 (StataCorp, College Station, Texas, USA).

RESULTS

A total of 193 patients were screened for enrolment; of them, 100 were enrolled. Ninety-three patients were excluded for declination of consent or non-availability of a qualified sonographer within the 6-hour inclusion window. On average, the examination took 11.3 min (range 2–30 min). Examinations were obtained in 97% of the patients for pupillometry, 96% for optic nerve sheath and 79.2% for transcranial Doppler.

The CT positive group was significantly older (51.7 IQR 22.4 vs 40.9 IQR 17.2 p=0.008) and had higher lactate levels (3.8 IQR 2.6 vs 2.8 IQR 1.8 p=0.01) (table 1). As expected, the CT positive group had a lower GCS in the field and at initial presentation (p<0.001). Fifteen patients in the positive CT group had an ICP monitor placed (30.6%), only 4 of these had an ICP of >20. In this group, 93.8% had neurosurgery consultations. The distribution of injuries (table 1) is depicted.

All types of brain injuries were represented, the most common being subarachnoid haemorrhage (n=31, 63.2%) followed by subdural haemorrhage (n=27, 55.1%). Of all patients, 98% had more than one type of TBI (see online supplementary files). For the individual components of the non-invasive examination, ONSD was found to be non-significant between groups (p=0.15). NPi<3 was significantly lower in the CT positive group (p=0.02). With measurements of pupil size, variability was noted between nursing data (qualitative) and quantitative pupillometry data. Of the patients where comparison was possible (n=78), a >0.5 mm difference was detected in pupil size

Table 1 Demographics of patients with TBI and positive or negative radiological findings

	CT (+) (N=49)	CT (−) (N=51)	p Value
Age (mean, SD)	51.7 (22.4)	40.9 (17.2)	0.008
Mechanism (%)			
Assault	1 (2)	5 (9.8)	0.03
Blunt trauma	1 (2)	1 (2)	
Fall	22 (44.9)	11 (21.6)	
Gunshot wound	0	5 (9.8)	
Hanging	0	1 (2)	
Motorcycle crash	4 (8)	3 (5.9)	
Motor vehicle crash	12 (24.5)	15 (29.4)	
Pedestrian struck	9 (18.4)	6 (11.8)	
Stabbing	0	3 (5.9)	
Other	0	1 (2)	
Admission vital signs			
Systolic blood pressure	138.2 (53.3)	130.4 (30.3)	0.37
Diastolic blood pressure	73.3 (16.3)	76.5 (18.8)	0.36
Heart rate	87 (25.6)	90.7 (21.9)	0.44
SpO$_2$	98.6 (2.9)	99.0 (1.9)	0.39
Prehospital GCS (median, IQR)	4 (3–10)	4 (10–15)	<0.001
Eye	1 (1–3)	4 (3–4)	<0.001
Verbal	1 (1–2)	5 (3–5)	<0.001
Motor	2 (1–5)	6 (4–6)	<0.001
Admission GCS (median, IQR)	7 (3–11)	14 (10–15)	<0.001
Eye	1 (1–4)	4 (3–4)	<0.001
Verbal	1 (1–3)	4 (2–5)	<0.001
Motor	4 (1–5)	6 (5–6)	<0.30
Selected laboratory findings (mean, SD)			
Lactate	3.8 (2.6)	2.8 (1.8)	0.01
INR	1.21 (0.2)	1.1 (0.4)	0.24
Base excess	−4.2 (3.3)	4.1 (4.0)	0.93
PaO$_2$	171.9 (92.5)	167.1 (77.5)	0.82
Haemoglobin	11.9 (2.5)	12.5 (2.3)	0.21
Bicarbonate	22.8 (5.7)	23.3 (4.5)	0.57
Intoxication			
Alcohol	17 (34.7)	21 (41.2)	0.5
Drugs			
Benzodiazepines	1 (2)	1 (2)	
Cannabinoids	4 (8.1)	11 (21.6)	
Cocaine	2 (4.1)	5 (9.8)	
Methadone	4 (8.1)	4 (7.8)	
No drugs	(77.7)	(58.8)	0.001

GCS, Glasgow coma scale; TBI, traumatic brain injury.

69% of the time and a difference of >1 mm 39% of the time. In the TCD data, mean PI was higher in the CT-positive group (1.44±0.83 vs 0.90±.24, p=0.002), and the number of patients with a PI of >1.3 was significantly higher in the CT-positive group (35 patients (71.4%) vs 26 patients (51%), p=0.04). EDV and the number of patients with EDV<30 were not significantly different (p=0.08, p=0.27 and p=0.19) (table 2).

Results of logistic regression for predicting positive radiographic findings, using bootstrapping, are presented in table 3. Sensitivities, specificity, PPV and NPV for selected variables are presented in table 4. Receiver operator characteristics (ROC) curve was calculated for selected variables at predicting a +CT (figure 1). NPi<3 was the most predictive of a brain injury in this group. Lactate remained a critical variable to the model and was elevated in 100% of our brain-injured group.

DISCUSSION

We were able to successfully demonstrate that TCD ultrasonography and QPR are feasible as an early assessment tools in trauma patients. It was used across a variety of patients, mechanisms and types of brain injury without compromising care and represents the first study of its kind in the literature evaluating each component in tandem as a predictor of a positive CT scan. Given that 94% of the positive CT images led to either neurosurgical consultation or intervention, a portable early prediction tool such as the tested examination could augment prehospital triage and facilitate care in trauma centres.

Quantitative pupillometry
Pupillary changes are a critical component of the trauma assessment, predict changes in neurologic status and may be the only detectable sign of deterioration.[15] Despite this, there is no standard on how pupil reactivity is measured—light, power, distance from the eye, and terminology (sluggish/brisk) are all variable and qualitative.[16]

Interobserver variability in estimation of pupil diameter is high, calling for a more quantitative assessment of the pupil.[17] Even at robust trauma centres, with excellent and experienced nurses, size discrepancy between nursing measurements of the pupil and the QPR measurements commonly occurred and are troubling. Approximately 40% of the patients had over 1 mm of difference between clinical and quantitative exams. As a critical component of the neurologic examination, standardising and quantifying the examination may be beneficial.

In our study, the NPi was decreased in the CT positive group (below the normal cut-off value of 3). This corresponded to an OR of 2.9 for predicting brain injury and a specificity of 82.4%. Of all of the variables, a low NPi was the most predictive.

Transcranial Doppler
TCD serves as a non-invasive technique to describe intracerebral blood flow in haemorrhage, cerebral vasospasm, autoregulation and has been used to guide therapy.[18–20] It commonly used in patients with subarachnoid haemorrhage but is not widely used in trauma. Up to 80% of the TBI patients can have TCD derangements in the early post-traumatic period and can therefore be useful in guiding management decisions.[21] Elevations in the PI and decreases in the diastolic flow velocity (FVd) may reflect rising ICP, or downstream resistance, and increased flow velocity (FV) can diagnose vasospasm.[22]

Our data demonstrate that a 'snap shot' of MCA flow dynamics is feasible and predicative of TBI. MCA mean FV standards are well described, as are PI ((FVs-FVd)/FVm) ranges.[23] Abnormal PI values in trauma patients range from 1.2 to 1.4 in the literature.[20 24 25] We elected to use 1.3 as our threshold value.

PI was higher in the CT-positive group. The number of patients with a PI value of >1.3 was also significantly higher in the CT-positive group. EDV, contrary to most literature, did not predict a positive CT in our study.

The relationships between MCA velocities and various brain injuries are poorly defined and are dependent on systemic blood pressures, degree of ICP elevation, cerebral vasospasm (influenced by pCO2 levels) and degree of cerebral dysregulation. Despite this, we feel that TCD may have a role in early trauma evaluation and that an isolated PI of >1.3 should be followed up with early CT imaging.

Optic Nerve Sheath Diameter
The retrobulbar segment of the optic nerve sheath is a continuation of the subarachnoid space, and elevated intracranial

Table 2 Findings in TBI patients with radiographic versus no radiographic CT findings

Parameter	CT (+) (N=49)	CT (−) (N=51)	p Value
Mean right ONSD (SD)*	0.54 (0.08)	0.51 (0.11)	0.14
Mean left ONSD (SD)*	0.54 (0.09)	0.52 (0.09)	0.26
Mean sheath diameter (bilateral; SD)	0.54 (0.71)	0.52 (0.09)	0.15
PI >1.3	35 (71.4)	26 (51)	0.04
Mean PI	1.44 (0.83)	0.90 (0.24)	0.002
NPi <3.0	19 (38.8)	9 (17.7)	0.02
Maximal pupil size, right (mean, SD)	3.10 (1.4)	2.8 (1.1)	0.23
Maximal pupil size, left (mean, SD)	3.24 (1.5)	2.7 (1.0)	0.03
Right pupil reactivity (mean, SD)	10% (10%)	15% (7.2%)	0.004
Left pupil reactivity (mean, SD)	10.3% (10.8%)	13.2% (6.5%)	0.07
Mean PSV, right (SD)	97.7 (29.1)	67.7 (7.4)	0.02
Mean PSV, left (SD)	94.3 (23.5)	71.2 (5.7)	0.01
Mean EDV, right (SD)	28.9 (15.5)	35.9 (14.2)	0.08
Mean EDV, left (SD)	30.2 (19.1)	34.8 (14.2)	0.27
EDV <30 (%)	14 (28.6)	9 (17.7)	0.19
EDV <40 (%)	22 (57.9)	27 (43.6)	0.16

*The average of three sequential measurements.
EDV, end-diastolic velocity; NPi, neurological pupil index; ONSD, optic nerve sheath diameter; PI, pulsatility index; PSV, peak systolic velocity; TBI, traumatic brain injury.

Table 3 Results of logistic regression analysis for the prediction of positive radiographic findings

Variable	OR	95% CI*	p Value
Age >40	1.76	0.75 to 4.2	0.19
PI>1.3	1.71	0.65 to 4.51	0.27
NPi<3.0	2.9	1.1 to 7.61	0.03
Lactate	1.3	0.99 to 1.68	0.54

*Bootstrapped 95% CI. CIs were calculated with bootstrapping (1000 replications).
N=100.
NPi, neurologic pupillary index; PI, pulsatility index (TCD).

Table 4 Sensitivities, specificities, PPV, and negative predictive value (NPV) for selected objective parameters for predicting positive radiological findings in patients with TBI

Parameter	Sensitivity (%)	Specificity (%)	ROC	PPV (%)	NPV (%)
GCS<8	67.4	84.3	0.76	80.5	72.9
PI>1.3	71.4	49	0.60	57.4	64.1
NPi<3.0	38.8	82.4	0.61	67.9	58.3
EDV<30	28.6	82.4	0.55	60.9	54.6
ONSD >0.60	26.5	74.5	0.51	50	51.4
Lactate	2.0	100	0.67	100	51.5

EDV, end diastolic velocity (TCD); NPi, neurologic pupillary index; PI, pulsatility index; ONSD, optic nerve sheath diameter.

pressure is transmitted behind the eye and can be visualised by ultrasound with relative ease.[26] Sonographic assessment of optic nerve oedema using ONSD correlates with ICP with sensitivities of 74–95% and specificities of 74–100%.[27] ONSD US has been shown to be consistent with regard to reproducibility, accuracy, interobserver agreement and has been validated against MRI as a gold standard.[28] 'Normal' ONSD is a subject of debate, but it is generally agreed that an ONSD below 5 mm is considered normal.[27 29] Prior studies all have small sample size, heterogeneous populations, lack of power and are limited in universal applicability (single expert user, etc).[30] We evaluated ONSD as a portion of our non-invasive examination. This represents the largest ONSD data set in the trauma literature, with 100 patients imaged, 556 separate data points and multiple providers performing the ultrasound. We noted no statistical difference between the positive CT and negative CT groups for ONSD. While 15 patients in the positive CT group had an ICP monitor placed (36%), only 4 had opening pressures over 20. The ONSD in these patients averaged 5.6, 4.48, 5.2 and 5.03 mm for opening pressures of 28, 25, 30 and 20, respectively. This small number of patients precludes statistical analysis, but these ONSD values are less than expected for the elevation of ICP.

We noted a higher than expected ONSD (>5 mm) in both the non-injured group and injured groups in the absence of elevated ICP. Patients in both groups commonly had scleral thickening or ultrasonic evidence of papilledema, again without evidence of elevated ICP clinically or radiographically. This has been described previously in trauma[31] as a finding representing inflammation. It is possible that trauma and resuscitation increase the ONSD via unknown mechanisms (eg, inflammation or simple oedema) and are not necessarily reflective of elevated ICP or brain injury. It is also possible that this could be reflective of a neuropathologic process not able to be seen on CT scan caused by mild TBI. This warrants further study, as it clearly negatively impacts the utility of ONSD US as a bedside examination in trauma.

Full examination
We attempted to identify an additive effect of the entire non-invasive examination. Applying logistic regression to the tested variables (PI>1.3, NPi <3) and adding age and lactate, we attempted to create a preliminary predictive model to identify brain injury (positive head CT). ROC analysis for this model was 0.7181 (figure 1). As a means of comparison, GCS has been shown to have an ROC between 0.77 and 0.88 for predicting mortality in severe TBI[32 33] and an ROC of 0.446–0.643 in mild TBI for predicting abnormal CT findings.[34] This places the ROC for the tested variables in line with other prediction models. While not more accurate than GCS by ROC criteria,
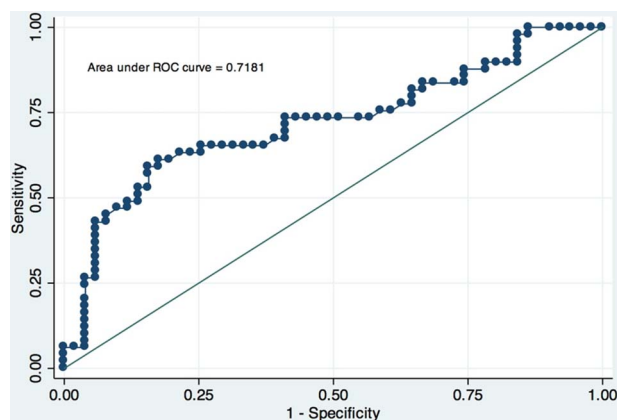
Figure 1 ROC curve was calculated for selected variables at predicting a positive CT. Variable were age >40, Lactate, NPi<3, PI>1.3.

this test is more objective and in theory may be less subject to misinterpretation than the GCS.

Finally, we suggest a simple scoring heuristic predicting brain injury (figure 2). This tool should be regarded as highly preliminary. Using this scoring system, on a scale of 0–4, patients meeting the most severe criteria have a 99.5% chance of having a positive CT scan. A single positive value from the tested examination predicts an 82.3–88.7% chance of having a CT-verified brain injury.

While preliminary, a non-invasive imaging strategy such as this may have clinical utility. It could assist in triage to a trauma centre, arranging the order of events in the resuscitation bay, or alerting the team to a high likelihood of brain injury. Age plays a large role in this model, as does lactate. Without lactate as a variable, the ROC is less predictive at 0.61. We interpret this

simply to imply that the model is not accurate unless the patient is severely injured, as evident by an elevated lactate. If a patient is healthy and not injured, a positive non-invasive neurologic examination has no clinical implication. An injured patient over 40, however, with a positive non-invasive examination, is at high risk of having a brain injury and should be triaged accordingly. On the contrary, the absence of any non-invasive findings does not rule out injury, and a high level of clinical suspicion must be maintained.

Feasibility

The tested examination is easy to perform accurately and carries no negative impact to the patient. The examination takes 11 min on average. Pupillometry and ONSD data were obtainable in almost all patients (97% and 96%, respectively). TCD was obtainable 79.2% of the time in the injured group, and 73.1% of the time in the non-injured group. This is consistent with the literature, where a TCD window is unobtainable 10–20% of the patients.[22] As a testament to the portability of the examination, several tests were obtained in the operating room, while the patients were undergoing torso, abdominal or extremity operations.

Limitations

This study has several limitations. With half of the screened patients not enrolled (declined consent or non-availability of sonographer), there may be the addition of selection bias. Most ultrasound literature describes a convenience sample as clinical expertise is not universally available. Likewise, in our study, this limitation was primarily manpower driven.

Ultrasound is operator dependant adding variability to the data. We attempted to mitigate this in two ways. We had multiple providers perform the exams (most literature identifies single expert user performing all exams), and we took multiple images of each data point, allowing for internal review and QA.

Exams were performed without explicit knowledge of the patient's diagnosis or prognosis (in the trauma bay) in an effort to minimise any bias. Results were de-identified and assigned a study label, and only after de-identification were images measured and analysed. These methods should have distributed variability evenly and acted to 'blind' the study.

While it is the largest study of its kind, the clinical numbers are still small for robust statistical comparison. In the statistical analysis, the model to identify predictors of positive CT findings was based on non-missing data for all variables. Bootstrapping can not only overcome this somewhat but can also amplify bias. This scoring model, again, is highly preliminary. Further studies with larger numbers are necessary to validate this model.

CONCLUSION

In the management of the brain-injured patient, early diagnosis and treatment equal better outcomes. The tested non-invasive examination shows promise as a diagnostic tool to predict brain injury, allowing accurate triage and care. It can be performed early in the patient's care. Increased exposure and experience with the test will only improve its utility and accuracy, similar to the evolution of the FAST examination as a point of care test. While this study is limited by small sample size, it is the largest study of its kind evaluating non-invasive measurements of brain injury and the first of its kind to analyse them as a combination test. The implications for the rural, austere or military settings, where resources are limited, may be important. Further evaluation is warranted to validate the accuracy, repeatability and utility of this non-invasive neurologic examination at predicting the need for interventions.

Parameter	Response	Scoring Weight
Lactate	1 to <2	-0.3
	>2 to <3	0 *
	>3 to <4	0.3
	>4	1.7
Pulsatility Index > 1.3	1	0.5
	0	0
NPI < 3.0	1	1
	0	0
Age > 40	1	0.5
	0	
Total Score		/4

* Reference (mean lactate of 2.5)

Risk Stratification Based on Score:

Score	Risk of Positive CT finding
0	73%
0.5	82.3%
1	88.7%
1.5	93.1%
2	95.8%
2.5	97.5%
3	98.5%
3.5	99.1%
4	99.5%

Figure 2 Suggested scoring heuristic for predicting a positive radiological finding in a patient with TBI. Note: this scoring rule is based on preliminary data, and requires validation in a larger data set.

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