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Original Contribution

# Comparison of quantitative EEG to current clinical decision rules for head CT use in acute mild traumatic brain injury in the ED☆,☆☆,★

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ABSTRACT

*Study objective:* We compared the performance of a handheld quantitative electroencephalogram (QEEG) acquisition device to New Orleans Criteria (NOC), Canadian CT Head Rule (CCHR), and National Emergency X-Radiography Utilization Study II (NEXUS II) Rule in predicting intracranial lesions on head computed tomography (CT) in acute mild traumatic brain injury in the emergency department (ED).
*Methods:* Patients between 18 and 80 years of age who presented to the ED with acute blunt head trauma were enrolled in this prospective observational study at 2 urban academic EDs in Detroit, MI. Data were collected for 10 minutes from frontal leads to determine a QEEG discriminant score that could maximally classify intracranial lesions on head CT.
*Results:* One hundred fifty-two patients were enrolled from July 2012 to February 2013. A total 17.1% had acute traumatic intracranial lesions on head CT. Quantitative electroencephalogram discriminant score of greater than or equal to 31 was found to be a good cutoff (area under receiver operating characteristic curve = 0.84; 95% confidence interval [CI], 0.76-0.93) to classify patients with positive head CT. The sensitivity of QEEG discriminant score was 92.3 (95% CI, 73.4-98.6), whereas the specificity was 57.1 (95% CI, 48.0-65.8). The sensitivity and specificity of the decision rules were as follows: NOC 96.1 (95% CI, 78.4-99.7) and 15.8 (95% CI, 10.1-23.6); CCHR 46.1 (95% CI, 27.1-66.2) and 86.5 (95% CI, 78.9-91.7); NEXUS II 96.1 (95% CI, 78.4-99.7) and 31.7 (95% CI, 23.9-40.7).
*Conclusion:* At a sensitivity of greater than 90%, QEEG discriminant score had better specificity than NOC and NEXUS II. Only CCHR had better specificity than QEEG discriminant score but at the cost of low (<50%) sensitivity.


## 1. Introduction

According to the Centers for Disease Control and Prevention, approximately 80% of the 1.7 million patients who suffer traumatic brain injury (TBI) annually in the United States are treated and discharged from the emergency department (ED) [1]. An overwhelming majority of these patients are considered mild with Glasgow Coma Score (GCS) of 13 to 15 [2].

There has been a reported increase in incidence of TBI-related ED visits to more than 14% from 2002 to 2006 [1]. This surge in incidence of ED visits has translated into an increased utilization of computed tomography (CT) for evaluation of minor head trauma in the ED. Because the current clinical decision rules for head CT utilization in mild TBI have high sensitivity at the cost of low specificity, most of these patients had negative scans [3]. This increased use of CT not only is an economic burden and adds to ED overcrowding but also has long-term implications of radiation, explicitly malignancy, with an estimated incidence of 1 in 1000 to 2000 individuals [3,4].

The New Orleans Criteria (NOC), the Canadian CT Head Rule (CCHR), and the National Emergency X-Radiography Utilization Study II (NEXUS II) Rule are some of the most widely used and validated decision rules in clinical practice by emergency physicians [5–8]. Numerous external validation studies have corroborated that these decision rules have similar

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**Table 1**
Sensitivity and specificity of NOC, CCHR, and NEXUS II Rule in predicting intracranial lesions on head CT in external validation studies

| | Stein et al [11] | | Ro et al [8] | | Smits et al [13] | |
|---|---|---|---|---|---|---|
| | Sensitivity (95% CI) | Specificity (95% CI) | Sensitivity (95% CI) | Specificity (95% CI) | Sensitivity (95% CI) | Specificity (95% CI) |
| NOC | 99.0 (98.0-100.0) | 33.0 (32.0-34.0) | 90.7 (83.9-95.3) | 23.4 (19.6-27.5) | 98.3 (94.0-99.5) | 5.6 (2.7-8.8) |
| CCHR | 99.0 (98.0-100.0) | 47.0 (46.0-48.0) | 72.9 (63.9-80.7) | 41.3 (36.8-45.9) | 83.4 (77.7-87.9) | 39.4 (36.0-42.8) |
| NEXUS II | 97.0 (96.0-98.0) | 47.0 (46.0-48.0) | 83.9 (76.0-90.0) | 36.0 (31.6-40.5) | Not studied | Not studied |

high sensitivities and comparable lower specificities [8–13]. Table 1 highlights the results of some of these external validation studies. The clinical policy on neuroimaging and decision making published in 2008 by the American College of Emergency Physicians' panel on mild TBI has also discussed the limitations of these decision rules, as these rules must be applied within the parameters of their inclusion criteria such as loss of consciousness or amnesia [14].

There is growing evidence that quantitative electroencephalogram (QEEG) can be used to evaluate minor head trauma, as it can gauge subtle abnormalities in brain electrical activity associated with mild TBI [3,15,16]. Recent data have suggested its usefulness in evaluating players with sports-related concussions and assessments of postconcussive syndrome (PCS) [17–20]. With the advent of waveform recognition algorithm and automated EEG analysis, the viability of using QEEG in the acute setting is possible [3,21]. Whether QEEG can be used efficiently in the ED environment as a better predictor of intracranial lesion than the current decision rules for head CT utilization in mild TBI has yet to be answered.

The objective of this study was to compare the performance of a handheld QEEG device to NOC, CCHR, and NEXUS II Rule in predicting intracranial lesions on head CT in acute mild TBI.

## 2. Methods

### 2.1. Study design and setting

A convenience sample of patients was enrolled from July 2012 to February 2013 in this prospective observational study at 2 urban academic EDs in Detroit, MI. Detroit Receiving Hospital is a 268-bed, level I trauma center, whereas Sinai-Grace Hospital is a 337-bed, level II trauma center. Both hospitals serve inner-city populations and have approximately 100 000 ED visits annually. Both clinical sites received approvals from Wayne State University's Institutional Review Board before any subject enrollment. Written informed consent was obtained from all subjects and/or legally authorized representative before QEEG data acquisition. The Conley criteria were used to assess the capacity of the subject to give informed consent [22].

### 2.2. Selection of participants

A convenience sample of patients between the ages of 18 and 80 years who presented within 24 hours of acute blunt head trauma, with a GCS of 13 to 15, and had a head CT ordered as part of their standard of care was enrolled. Patients with forehead lacerations that prevented electrode application were excluded. Other exclusion criteria were dementia, Parkinson disease, multiple sclerosis, seizure disorder, brain tumors, history of brain surgery, psychiatric disorder for which there was a prescribed psychiatric medication taken on a daily basis, substance dependence, history of transient ischemic attack or stroke within the last year, open head injury, pregnant women, and prisoners. Research assistants trained on the device were staffed in the ED, screening for patients 24 hours per day, 7 days per week.

### 2.3. Procedures, measurements, and outcomes

Computed tomographic interpretations, made by neuroradiologists/radiologists as standard of care, were used at both clinical sites for classifying subjects into CT-positive or -negative groups. These interpretations were blinded to EEG results and all other patient information, except the head injury indication for the scan. The CT scans were considered positive if they had trauma-induced intracranial lesions, such as petechial hemorrhages, parenchymal bleeds, subarachnoid hemorrhages, cerebral contusions, and epidural and subdural hematomas. The QEEG data acquisition on the device was done by ED research assistants who were trained to use the device but did not have prior EEG experience. The QEEG data acquisition and head CT were both done within 24 hours of injury.

All patients underwent 5 to 10 minutes of closed-eyes resting EEG acquisition on a handheld device under development by BrainScope. These EEG recordings were collected with frontal montage using self-adhesive, pregelled electrodes on a single-use headset. Frontal electrode sites of the International 10/20 system were used, which included FP1, FP2, AFz, F7, and F8, referenced to linked ears. All electrode impedances were below 10 kΩ before data acquisition. Electrode placement was accomplished in all cases in less than 5 minutes. Automatic artifact rejection was used during EEG data acquisition to remove any contamination, such as that from muscle or eye movements.

The first outcome measure of the study was to determine a QEEG discriminant score that could maximally classify subjects with intracranial lesions visible on head CT. The second outcome measure compared the performance (sensitivity and specificity) of this discriminant score to NOC, CCHR, and NEXUS II Rule for accuracy in prediction of positive CT findings. The variables that make up these clinical decision rules were also collected prospectively at the time of EEG evaluation. Table 2 shows the eligibility criteria and the indications for head CT adopted in these clinical decision rules.

### 2.4. Quantitative EEG and statistical analysis

Off-line quantitative analysis of this artifact-free EEG data was done, features extracted, age regressed, and input to a previously established discriminant algorithm to determine the binary classification for each case. This algorithm was derived using iterative methods and cross-validation (based on features extracted from algorithm development database) to construct this binary discriminant classification algorithm. The algorithm consists of weighted, multivariate grouping of selected linear and nonlinear features of brain electrical activity that statistically distinguish normal brain activity from brain activity seen in CT-positive TBI subjects [3,15]. The result is articulated as a discriminant score, using a threshold calculated from the receiver operator curve of the discriminant function, and is used to make a binary classification of the patients with the highest probability of being CT positive [15,23].

## 3. Results

We enrolled 152 patients with blunt head trauma during the study period. The average age of the patients was 36.6 years (SD ± 15.2) and

**Table 2**
Clinical decision rules for using head CT in mild TBI with reported validity of the original studies

| Decision rule | Indications for head CT | Inclusion criteria | Exclusion criteria | Sensitivity (95% CI) | Specificity (95% CI) |
|---|---|---|---|---|---|
| NOC [5] | Headache, vomiting, seizure, intoxication, short-term memory deficit, age >60 y, or injury above clavicles | Blunt trauma, LOC or amnesia, GCS 15, age >3 y, injury within the past 24 h | Acute focal neurologic deficit | 100.0 (95.0-100) | 25.0 (22.0-8.0) |
| CCHR [7] | High-risk patients: GCS score <15 at 2 h postinjury, suspected skull fracture, any sign of basal skull fracture, vomiting (≥2 times), age ≥65 y<br>Medium-risk patients: retrograde amnesia >30 min, dangerous mechanism (pedestrian vs motor vehicle; ejected from motor vehicle; fall from height >1 m or 5 stairs) | Blunt trauma, LOC or amnesia or disorientation, GCS 13-15, age ≥16 y, injury within past 24 h | Obvious penetrating or depressed skull fracture, acute focal neurologic deficit, seizure before ED assessment, on anticoagulation, bleeding tendency | 98.4 (96.0-9.0) | 49.6 (48.0-1.0) |
| NEXUS II [6] | Recurrent or forceful vomiting, evidence of significant skull fracture, age ≥65 y, scalp hematoma, neurologic deficit, altered level of alertness, abnormal behavior, coagulopathy | All blunt trauma | A delayed presentation, without blunt trauma | 95.2 (92.2-7.2) | 17.3 (16.5-8.0) |

LOC, loss of consciousness.

mean the GCS was 14.9, with 68.4% male. A total of 82.2% were African American; 15.1%, white; and 2.6%, Hispanic. A total of 66.4% had loss of consciousness, and 32.2% had altered mental status. Blood alcohol levels were measured in 57.9% of the patients and were found to be abnormal in 50% of them with mean levels of 200 mg/dL (SD ± 104). Similarly, drug screen was ordered in 43.4% of these patients and was found to be abnormal in 53% of them. A total of 46.7% of the patients were involved in motor vehicle accidents, 30.2% were assaulted, 18.5% had fall as the mechanism of injury, 3.3% were pedestrians struck by vehicle, and 1.3% had bicycle accidents. All patients underwent head CT as standard of care in the ED, and 26 (17.1%) patients had acute traumatic intracranial lesions visible on CT.

Quantitative electroencephalogram discriminant score greater than or equal to 31 was found to be a good cutoff to classify patients with positive head CT, with area under receiver operating characteristic curve = 0.84 (95% confidence interval [CI], 0.76-0.93). Table 3 compares the sensitivity, specificity, positive predictive value, negative predictive value, and likelihood ratio of the QEEG discriminant score greater than or equal to 31 with the 3 clinical decision rules.

Neurosurgical intervention was needed in 2 patients with positive findings on head CT. These were identified by all 3 decision rules and had a QEEG discriminant score greater than or equal to 31. A QEEG discriminant score less than 31 was found in 3 patients with positive findings on head CT. These findings were (1) subarachnoid hemorrhage at the anterior inferior aspects of the bilateral frontal lobes, (2) acute subdural hematoma in the right posterior temporal region just above the tentorium, and (3) acute subdural hemorrhage seen along the right temporal region extending to the Sylvian fissure. All of these findings were classified as “Diffuse Injury II” by using the Marshall CT Classification [24]. None of these patients required neurosurgical intervention and were discharged home. All 3 patients were identified by NOC and NEXUS II rule; only one met the criteria for CCHR.

## 4. Discussion

In 2008, the American College of Emergency Physicians’ panel on neuroimaging and decision making had formulated an evidence-based clinical policy to answer the foremost challenge that emergency physicians face when patients present with minor head injury in the ED: who should they send to the scanner for a noncontrast CT? [14] We have tried to augment these recommendations with an electrophysiological test of quantified brain electrical activity that can detect brain injury in a patient population with a low pretest probability, as any practical and realistic application of these guidelines in the real world is restricted by physicians’ attitude and bias due to the prevailing malpractice litigation that hounds the health care system [8]. There is also growing evidence that shows increased utilization of head CT in this patient population following the implementation of some of these clinical decision rules [25–27].

Data from a previous study suggest that detectable functional abnormalities on EEG may appear before visible structural damage on CT imaging in patients with mild TBI [3,28]. Quantitative brain electrical activity has also shown to be highly accurate in identifying traumatic hematomas in minor head injury patients in a recent study by Hanley and colleagues [15]. The study also demonstrated significant correlation between QEEG-derived TBI index and the volume of blood in the hematomas [15]. O’Neil et al [3] have previously reported that the specificity of this QEEG-derived TBI index was twice as good as NOC with comparable sensitivity [3]. Since the publication of that study, the QEEG algorithm has been retrained; and the acquisition device has been

**Table 3**
Comparison of QEEG with NOC, CCHR, and NEXUS II Rule in predicting intracranial lesions on head CT

| | Sensitivity (95% CI) | Specificity (95% CI) | PPV (95% CI) | NPV (95% CI) | +LR (95% CI) | −LR (95% CI) |
|---|---|---|---|---|---|---|
| QEEG discriminant score | 92.3 (73.4-98.6) | 57.1 (48.0-65.8) | 30.7 (21.0-42.3) | 97.2 (89.6-99.5) | 2.1 (1.71-2.71) | 0.1 (0.03-0.51) |
| NOC | 96.1 (78.4-99.7) | 15.8 (10.1-23.6) | 19.0 (12.9-27.0) | 95.2 (74.1-99.7) | 1.14 (1.02-1.27) | 0.24 (0.03-1.79) |
| CCHR | 46.1 (27.1-66.2) | 86.5 (78.9-91.7) | 41.3 (24.0-60.8) | 88.6 (81.3-93.4) | 3.42 (1.86-6.27) | 0.62 (0.43-0.89) |
| NEXUS II | 96.1 (78.4-99.7) | 31.7 (23.9-40.7) | 22.5 (15.3-31.6) | 97.5 (85.5-99.8) | 1.40 (1.22-1.62) | 0.12 (0.01-0.85) |

PPV, positive predictive value; NPV, negative predictive value; LR, likelihood ratio.

remodeled to reduce noise, and muscle and eye movement artifacts. The previous study had also used free electrodes that needed to be gelled before application [3]. In our study, we have used a single-use headset, which had self-adhesive, pregelled electrodes that made the application time considerably less.

Our data show that CCHR had the least sensitivity of all the clinical decision rules. This low sensitivity was also reported in a study by Ro et al [8] and can be explained by the stringent eligibility criteria of CCHR that define minor head injury requiring CT evaluation as witnessed loss of consciousness, amnesia, or disorientation with GCS 13 to 15 and also do not use high-prevalence variable such as headache, which is a criterion in NOC [5,7,8].

Although our data tried to identify neurologically intact, seemingly well patients that have a visible traumatic intracranial lesion on head CT, the ability to define those who will end up with PCS remains elusive. In the future, we would conduct neuropsychological testing at short- and long-term follow-ups in these patients to see if electrophysiological abnormalities detected by QEEG in the ED can predict PCS.

In summary, at a sensitivity of greater than 90%, QEEG discriminant score had better specificity than NOC and NEXUS II in predicting intracranial lesions on head CT in acute mild TBI in the ED. Only CCHR had better specificity than QEEG discriminant score but at the cost of low (<50%) sensitivity.

### 4.1. Limitations

This study focused on the performance of the 3 most extensively used and validated clinical decision rules [8]. Review of the literature shows other decision rules such as the Neurotraumatology Committee of the World Federation of Neurosurgical Societies [29], the National Institute of Clinical Excellence [30], and the Scandinavian Neurotrauma Committee guidelines [31] that have not been studied as extensively in external validation studies and were not compared with the QEEG discriminant score in this study. The fact that the study sample was not independent of the algorithm development population is also a potential limitation. However, because the study population represents only a very small percentage of the development database, less than 10%, the potential for overestimation is very small. The moderate sample size of the study is another limitation; BrainScope Company, Inc, the developer of the QEEG acquisition device and the algorithm, has recently sponsored a multicenter clinical trial (ClinicalTrials.gov Identifier: NCT01556711) that has completed enrollment with a better sample size of subjects with minor head trauma but did not compare the QEEG discriminant score with all 3 decision rules. Our sample size also had a relatively high rate of CT-positive subjects in a low-risk patient population (mild TBI). This relatively high rate can be explained by the inclusion criteria that only allowed enrollment of subjects that got head CT as part of their standard of care.

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