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Performance of a new portable near-infrared spectroscopy device for detection of traumatic intracranial hematoma

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ABSTRACT

Introduction: We report results of a newly developed portable near-infrared spectroscopy (NIRS) based point-of-care device CEREBO® to detect traumatic intracranial hematoma (TICH).
Materials and methods: Patients with alleged history of head injury visiting emergency room were enrolled. They were examined consecutively for the presence of TICH using CEREBO® and computed tomography (CT) scans.
Results: A total of 158 participants and 944 lobes were scanned, and 18% of lobes were found to have TICH on imaging with computed tomography of the head. 33.9% of the lobes could not be scanned due to scalp lacerations. The mean depth of hematoma was 0.8 (SD 0.5) cm and the mean volume of the hematoma was 7.8 (11.3) cc. The overall sensitivity, specificity, accuracy, positive predictive value (PPV), and negative predictive value (NPV) of CEREBO® to classify subjects as hemorrhagic or non-hemorrhagic were 96% (CI 90 - 99%), 85% (CI 73 - 93%), 92% (CI 86 - 96%), 91% (CI 84 - 96%) and 93% (CI 82 - 98%) whereas to classify the lobes as hemorrhagic and non-hemorrhagic, the sensitivity, specificity, accuracy, PPV and NPV were 93% (CI 88 - 96%), 90% (CI 87 - 92%), 90% (CI 88 - 92%), 66% (CI 61 - 73%), and 98% (CI 97 - 99%) respectively. The sensitivity was highest at 100% (CI 92 - 100%) for the detection of extradural and subdural hematoma. The sensitivity for detecting intracranial hematoma including epidural, subdural, intracerebral and subarachnoid hematomas, of more than 2 cc was 97% (CI 93 - 99%) and the NPV was 100% (CI 99 - 100%). The sensitivity dropped for hematomas less than 2cc in volume to 84% (CI 71 - 92%) and the NPV was 99% (CI 98 - 99%). The sensitivity to detect bilateral hematomas was 94% (CI 74 - 99%).
Conclusion: The performance of currently tested NIRS device for detection of TICH was good and can be considered for triaging a patient requiring a CT scan of the head after injury. The NIRS device can efficiently detect traumatic unilateral hematomas as well as those bilateral hematomas where the volumetric difference is greater than 2cc.

Introduction

Traumatic Brain Injury (TBI) is considered to be a significant cause of mortality and morbidity. The global incidence of TBI is estimated to be around 939 cases per 100,000 population and around 69 million are known to be affected by TBI each year. Of these, a total of 55.9 million cases are registered as mild TBI each year and 5.48 million severe cases of TBI [1]. In India, TBI is one of the leading causes of neurological disability [2]. The duration between the time of injury and the onset of treatment directly correlates with the survival and recovery rates. The delay in the treatment can lead to secondary brain injury. One of the most critical factors responsible for secondary injury is traumatic intracranial hematoma (TICH), which if promptly treated can prevent death and disability. The probability of ICH is more in clinically moderate and severe TBI. Even in clinically mild TBI, the incidence of ICH ranges from 1.6% to 29.4% depending on the risk factors [3]. A timely and accurate diagnosis of TICH is critical for the early management of patients with TBI. Computerized tomography (CT) scan of the head is an investigation of choice for the de-

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tection of ICH. However, the concerns for CT scans are limited access, increased radiation exposure, and an inappropriate burden on healthcare resources [4,5]. It is therefore important for the emergency medical services or the trauma department to quickly triage trauma patients for further examination and treatment. Field triaging can help to determine the presence of intracranial hematoma in patients and thus screen these patients to be referred for CT scan. A portable ICH detection tool that is accurate, easy to use, and rapid will help to bring down unnecessary CT scans and also prompt the need for an urgent CT scan in patients with TBI. Handheld near-infrared spectroscopy (NIRS) devices have been developed for diagnosing TICH at the point of care. These devices have shown variable accuracy depending on the volume of TICH, type of TICH, and depth of TICH [6]. We performed this study to validate a newly developed portable NIRS-based point-of-care device, CEREBO® (Bioscan Research Pvt. Ltd, India) to detect different types of TICHs. We hypothesized that the performance of this newly developed device will be at par with other devices tested in other countries.

Materials and methods

Participants and ethics approval

The study was conducted according to the declaration of Helsinki, and received ethical approval from our Institute's Ethics Committee (No. NIMHANS/24th 2 ICE (BS & NS DIV.)/2021 dated September 1, 2020). Written consent was obtained for the data collection from the next available kin of the patients. The study was registered on ClinicalTrials.gov (NCT05189561) retrospectively. The study was a single-center observational study to test the diagnostic performance of an indigenously developed handheld NIRS device, CEREBO® to detect TICH, by comparing the findings of the NIRS exam to those of the admission CT scan. The study was performed from August 24, 2021, to October 31, 2021, at the Emergency Block of the National Institute of Mental Health and Neurosciences (NIMHANS), Bangalore, India. Patients with an alleged history of head injury were enrolled. The "standards for reporting diagnostic accuracy studies" (STARD) guidelines were followed (supplementary file).

Inclusion criteria

The study included both male and female patients between 18 and 65 years of age visiting the emergency block of NIMHANS with an alleged history of head injury and recommended a head CT scan. Participants formed a convenience series. Only those patients who arrived during the daytime duty of research fellows were included.

Exclusion criteria

Exclusion criteria included major scalp laceration, active bleeding, significant extracranial hematoma or skull abnormality, or any other condition that would not allow device placement. Participants with a history of brain surgery or neurologic disease as well as pregnant women were also excluded. Patients with CT scan findings of hematoma not due to acute TBI, e.g. chronic subdural hematoma, hypertensive bleeds, hemorrhagic infarcts, etc. were excluded. All patients who met inclusion criteria were examined sequentially for the presence of TICH using portable CEREBO® and CT scans (Fig. 1). The following CT scan findings were recorded: hematoma location (frontal, temporal, parietal, and occipital), hematoma type (epidural, subdural, intracerebral, and subarachnoid hemorrhage), and hematoma depth and volume. The

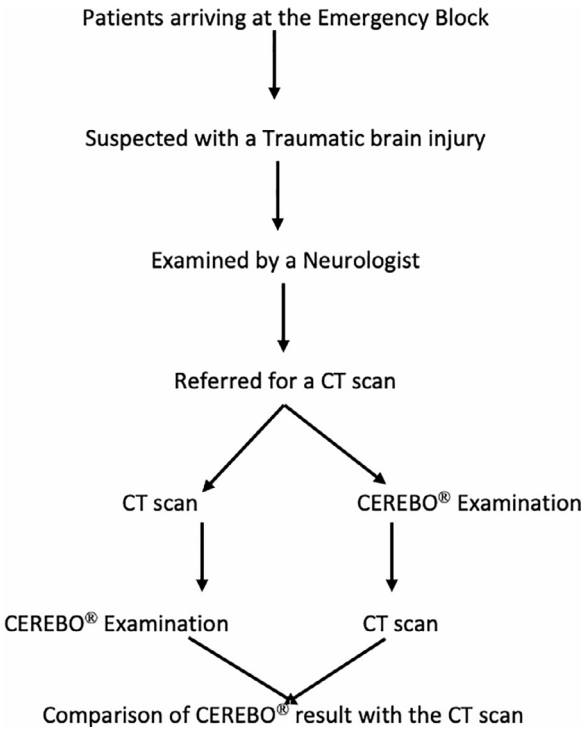

Fig. 1. Work flow of the study.

CEREBO® operator was blinded to the CT scan results. The independent biostatistician was not blinded to the results, enabling her to perform the statistical analysis.

NIRS examination

Principle

NIRS utilizes the near-infrared region of the electromagnetic spectrum. The basic principle of hematoma detection with NIRS is that absorption in the near-infrared range is relatively small and hemoglobin contributes to most of the tissue absorption; extravascular blood absorbs NIR light more than normal brain tissue since there is a greater concentration of hemoglobin in a hematoma. By comparing the backscattered or diffused optical signal I2 from the suspicious hematoma side and I1 from the non-hemorrhagic side, the optical density (OD) is calculated as OD=log10 (I1/I2) [7]. The high effectiveness of NIRS is due to its capability to penetrate and investigate the scalp, skull, and brain up to a certain depth non-invasively. Care was taken to limit the optical signal exposure for safe operation as per US FDA guidelines.

Data acquisition

CEREBO® was placed on the patient's head at eight different sites, four each on the left and right hemispheres at the frontal, temporal, parietal, and occipital lobes (Fig. 2). The procedure was performed by trained research fellows (RJ, MS, and BL). Once the device was placed on the scalp and triggered, data acquisition was automatic. Once the scan was completed, the buzzer tone and the green tick on the respective location indicated the same. A participant's head was scanned within 3–5 min at all eight sites. CEREBO® is designed to detect a hematoma volume >2 cc at a distance of 3–3.5 cm from the surface of the skull.

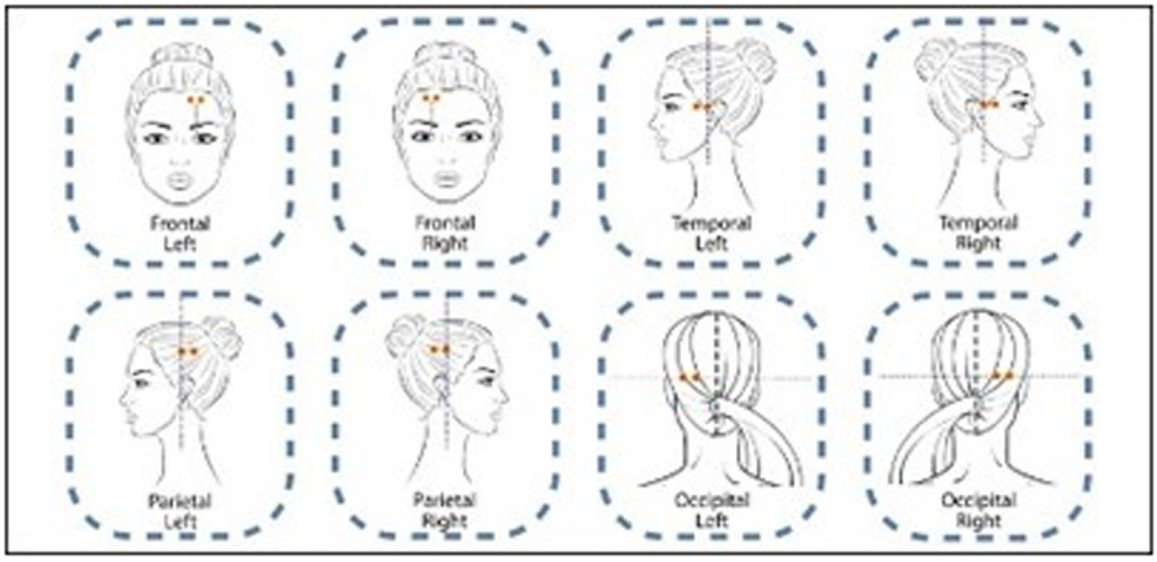

Fig. 2. Scanning sites by NIRS device.

Data processing and display

Once the scan is complete for at least two contralateral sites or lobe locations (for example, left frontal and right frontal) and the "OK" button is pressed, the data processing begins. The NIRS signals are processed through real-time noise cancelation and feature extraction algorithms to produce validated data point pairs of input and output signals (DPIO). A resultant value is computed for each scanned site using a machine learning algorithm that performs linear regression on validated DPIO. The logarithmic ratio of these resultant values corresponding to the left and right hemispheres generates the optical density ratio (ODR). A site is considered hemorrhagic whenever the absolute value of ODR is greater than or equal to 0.1. This ODR cut-off value was obtained based on the pilot study. Also, a positive ODR greater than or equal to 0.1 indicates that the hemorrhage is present on the right side while a negative ODR with an absolute value greater than or equal to 0.1 indicates that the hemorrhage is present on the left side. The presence of a hematoma is indicated by red and its absence as green on the corresponding site (Fig. 3).

CT scans evaluation

The CT scans were read by a neuroradiologist (GP) who was blinded to the CEREBO® results. Patients with CT scans showing pathologies not suggestive of acute TBI were excluded. The following parameters were recorded: location of hematoma, type of hematoma, depth of hematoma, and volume of hematoma. The sites of hematoma visible on the CT scan were categorized into frontal, temporal, parietal, or occipital. The type of bleeding was categorized into epidural hematoma (EDH), subdural hematoma (SDH), contusion/ intracerebral hematoma (ICH), or subarachnoid hemorrhage (SAH). The hematoma volume was calculated based on the formula A x B x C/2 as recommended by the Brain Trauma

Fig. 3. A. Picture of CEREBO® during scanning of one patient **B.** Representative image showing results of NIRS scan output.

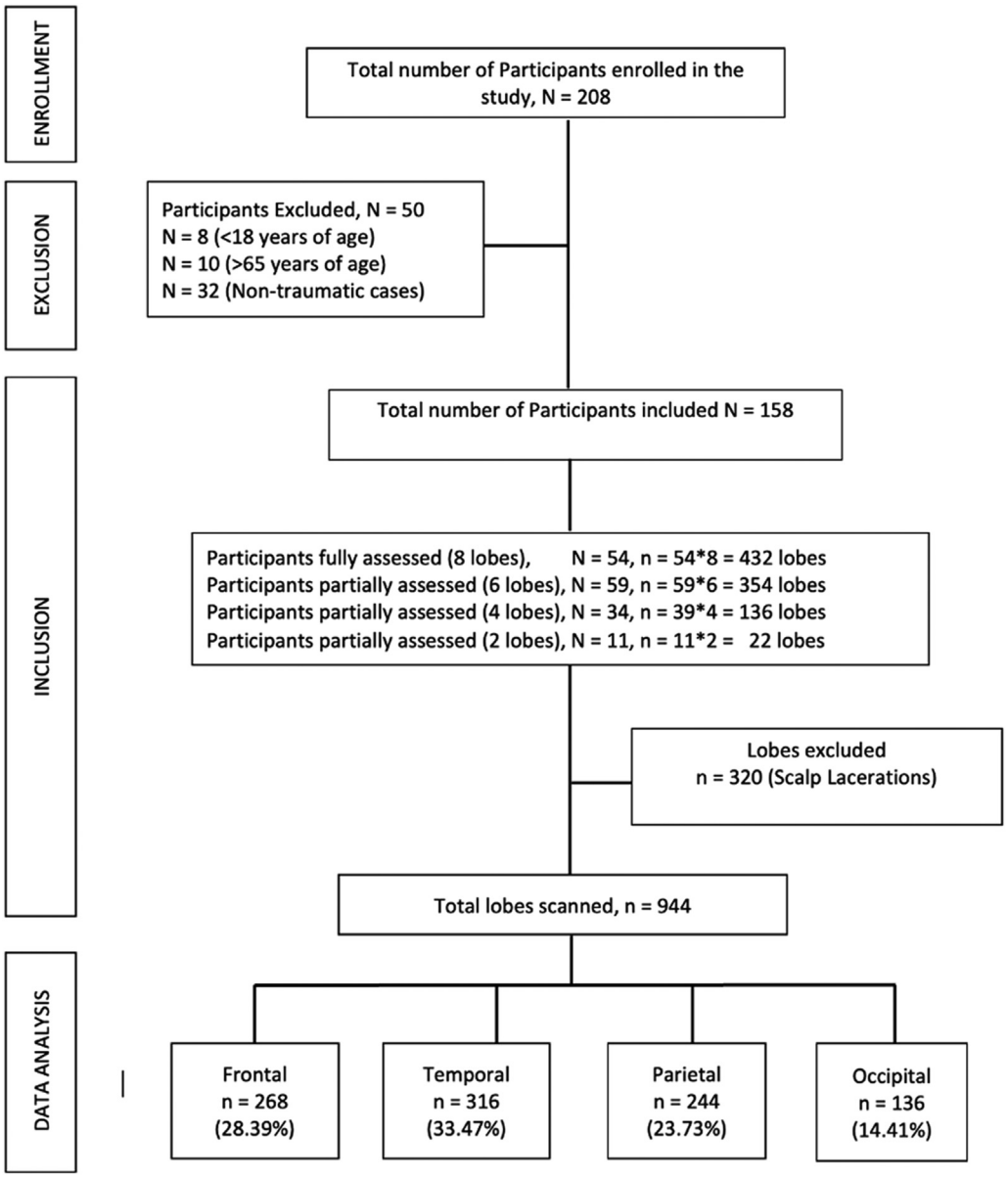

Fig. 4. Flowchart showing the inclusion of patients.

Foundation (BTF) guidelines for surgical management of TBI [8]. Combined hypodense and hyperdense components of contusion were used for the computation of the volume of cerebral contusions. When the hematoma extended beyond one of the locations, the volume at the individual location was determined. For volumetric analysis, hematomas were grouped into two classes - (1) volume $\leq$2 cc and (2) volume >2 cc. The depth of the hematoma was calculated from the outer table of the skull.

Statistical analysis

The primary objective of the study was to compute the sensitivity, specificity, accuracy, positive and negative predictive values, and positive and negative likelihood ratios of CEREBO® in comparison to the gold standard i.e., CT scan, and thus assess its efficacy to detect intracranial hematomas. The analysis was performed to classify each subject and then each lobe was scanned as hemorrhagic and non-hemorrhagic.

To analyze the classification accuracy of CEREBO® to classify each subject as hemorrhagic or non-hemorrhagic, the following steps were followed:

1. For each subject, CEREBO® generates multiple results corresponding to 2–8 brain sites as RED or GREEN, where RED is coded as TRUE and indicates the presence of hemorrhage while GREEN is coded as FALSE and indicates an absence of hemorrhage
2. For each subject, the multiple results generated in Step 1 are fed to an *OR* function in SPSS where the function is defined as

- RED *OR* RED = TRUE
- GREEN *OR* GREEN = FALSE
- RED *OR* GREEN = TRUE

Hence each Subject was assigned a TRUE or FALSE value indicating hemorrhagic or non-hemorrhagic subject respectively.

3. Similarly, the CT scan is also assigned a TRUE or FALSE by combining the result of individual brain sites via an *OR* function.
4. The result of CEREBO® scan is then compared with the CT scan for each subject.

To analyze the classification accuracy of CEREBO® to classify each lobe or brain site as hemorrhagic or non-hemorrhagic, the following steps were followed

1. Each lobe was considered an individual sample
2. CEREBO® generated the result of each lobe as RED or GREEN where RED is coded as TRUE or indicates the presence of hemorrhage and GREEN is coded as FALSE and indicates the absence of hemorrhage
3. Similarly, the CT scan assigns a TRUE or FALSE for each individual lobe or brain site.
4. The result of CEREBO® scan is then compared with that of the CT scan for each lobe

With a significance criterion of alpha = 0.05, and power = 0.90, the sample size was estimated based on the estimated sensitivity, specificity and prevalence of 0.95, 0.76 and 0.83 respectively from the pilot study (unpublished), of 44 patients which evaluated the diagnostic accuracy of CEREBO® to detect hemorrhages. The minimum sample size needed to detect a difference of 10% from the presumption value of specificity is $N = 132$. Thus, the obtained sample size of $N = 158$ is more than adequate for testing the sensitivity and specificity of CEREBO® to detect hemorrhages.

Results

A total of 208 patients were enrolled in the study. Fifty patients were excluded, 18 participants did not meet the inclusion criteria and 32 were diagnosed with other pathologies like chronic hematomas, nontraumatic hematomas, tumors with bleeding, intraventricular hemorrhage, and cerebral venous thrombosis, leaving data from 158 patients available for analysis. Assessment of all eight lobes was possible in 54 patients, only six lobes in 59 patients, only four lobes in 39 patients and only two lobes in 11 patients. Of 1264 ($158 \times 8 = 1264$ lobes) total brain sites (lobes) evaluations to be performed across all participants, we were able to access 944 sites. The remaining 320 (33.9%) lobes were inaccessible because of overlying scalp lacerations (Fig. 4). The mean age of the patients was 38 (SD 13.1) years comprising 86.1% males and the rest of females. The Glasgow coma scale (GCS) score was 14–15 in 47.5% of cases, 9–13 in 47.5%, and <9 in 5% of cases. The mean depth of the hematoma was 0.8 (0.5) cm from the outer table of scalp and the mean volume of the hematoma was 7.8 (11.3) cc. The commonest type of hematoma was intracerebral followed by subdural. The commonest site of hematoma was temporal followed by frontal (Table 1). For subject-wise analysis, a high sensitivity of 96% (CI 90 - 99%) was demonstrated (Table 2). For lobe-wise analysis, the overall sensitivity, specificity, accuracy, positive predictive value (PPV), and negative predictive value (NPV) were 93% (CI 88 - 96%), 90% (CI 87–92%), 90% (CI 88 - 92%), 66% (CI 61 - 73%), and 98% (CI 97 - 99%) respectively (Table 3 and 4). The false positivity rate was 33.9%, which means that the number of sites needed to scan is three to detect one site of hematoma of the CT scan. Based on the location of intracranial hematoma as revealed in the CT scan i.e. frontal, temporal, parietal, and occipital the sensitivity ranged from 93% to 100%, specificity ranged from 86% to 90%, and accuracy ranged from 87% to 90% (Table 4). Among the hematoma types, the sensitivity was highest at 100% (CI 90 - 100%) for the detection of EDH and SDH, while it was lowest at 79% (CI 60 - 92%) for the detection of SAH (Table 5). The sensitivity for detecting intracranial hematoma of more than 2 cc was 97%

Table 1
CT scan findings.

CT Scan Findings	Total lobes (sites) scanned, $n = 944$
Normal (non-hemorrhagic)	774 (82%)
Hematoma	170 (18%)
Type of hematoma	
• EDH	35 (20.6%)
• SDH	46 (27.1%)
• SAH	29 (17.1%)
• ICH/ Contusion	60 (35.3%)
Location of hematoma	
• Frontal	55 (28.4%)
• Temporal	66 (33.5%)
• Parietal	40 (23.7%)
• Occipital	9 (14.4%)
Depth of hematoma in cm	
• Mean (SD)	0.8 (0.5)
• Median	0.6
• Minimum	0.3
• Maximum	2.8
• First Quartile (25th percentile)	0.5
• Third Quartile (75th percentile)	0.8
Volume of hematoma in cc	
• Mean (SD)	7.8 (11.3)
• Median	6.7
• Minimum	1.6
• Maximum	66.6
• First Quartile (25th percentile)	3.4
• Third Quartile (75th percentile)	10.2

CT – computed tomography
.EDH – epidural hematoma
SDH – subdural hematoma.
SAH – subarachnoid hemorrhage ICH – intracerebral hemorrhage.
SD – standard deviation.

Table 2
Subject-wise performance of CEREBO®.

	Total number of patients scanned, $n = 158$
Sensitivity	0.96 (0.90 - 0.99)
Specificity	0.85 (0.73 - 0.93)
Accuracy	0.92 (0.86 - 0.96)
PPV	0.91 (0.84 - 0.96)
NPV	0.93 (0.82 - 0.98)
PLR	6.39 (3.50 - 11.70)
NLR	0.05 (0.02 - 0.13)

PPV – positive predictive value.
NPV – negative predictive value.
PLR - positive likelihood ratio.
NLR - negative likelihood ratio. The numbers in the bracket gives the 95% confidence interval calculated using the Clopper-Pearson exact method.

Table 3
2 × 2 table comparing the results of CEREBO® with that of the CT scan for number of sites (lobes) scanned.

	CT +	CT -	Total number of sites
CEREBO® +	158	81	239
CEREBO® -	12	693	705
Total	170	774	944

CT – computed tomography.

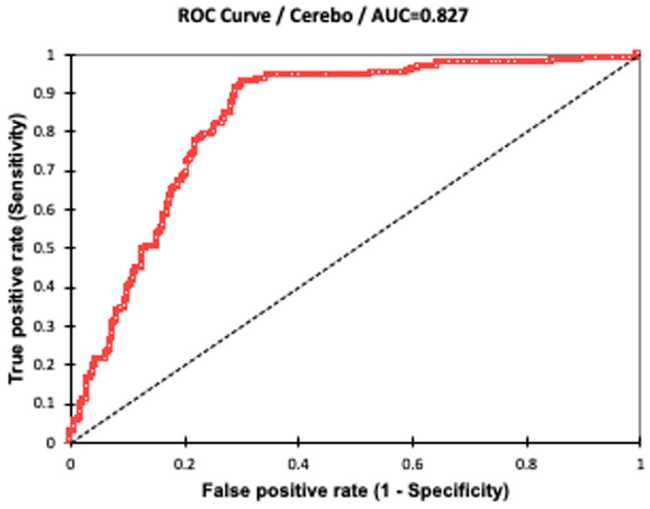

Fig. 5. ROC curve for detection of TICH in lobes by NIRS device.

(CI 93 - 99%) and the negative predictive value was 100% (CI 99 - 100%) (Table 6). Thirteen locations with intracranial hematoma were not detected by CEREBO® (Table 7 and Fig. 5). The ODR was less than the threshold of 0.1 in all these cases. Six of these were SAHs and seven were ICHs. Out of seven ICHs, four were less ≤2 cc in volume. One ICH was 12.7 cc and in a basifrontal location. Another was 21 cc in temporal location. In this case, the computed volume was of combined hypodense and hyperdense components of contusion. The third one was 13.3 cc in the parietal location. In this case, the majority of hematoma was in the temporal location, which was detected and the parietal portion of the hematoma was not detected.

An additional analysis was performed from the current dataset to determine optimal cut-off value of OD. The receiver operating characteristic (ROC) curve was used to evaluate the performance of the newly developed algorithm. A series of threshold values were obtained for all the lobes indicated as hemorrhagic or non-hemorrhagic by CEREBO®. The values were computed against the CT output of their respective lobes to find the cut-off value where the threshold demonstrates the best sensitivity and specificity. An optimal cut-off value of 0.095 was obtained for each lobe, resulting in sensitivity of 93% and specificity of 70% with an AUC of 0.827 (95% CI of 0.786 - 0.868), $p < 0.0001$. The high AUC establishes the capability of the algorithm to differentiate between the hemorrhagic and non-hemorrhagic lobes efficiently (Fig. 6). Future studies can be planned based on new cut-off value of 0.095.

Discussion

Intracranial hematoma is a significant contributor to secondary TBI and has shown to affect the prognosis after TBI [8]. An early diagnosis leading to prompt evacuation of TICH is recommended. The CT scan of the head is currently considered the investigation of choice for the detection of TICH in emergency settings. The CT scanner may not be available at all the health centers and with the first response paramedics' team. There is a need for an alternative portable device for the screening of patients who may have TICHs and triaging such patients for appropriate referrals. The handheld NIRS devices solve this purpose [7]. A few NIRS devices have been tried and their results have been reviewed [6,9,10]. In our present study, we validated the newly developed handheld NIRS device CEREBO® for the detection of TICH. The strength of our present study was a relatively large number of sample size and analysis of each anatomical site for the detection of TICH. The sensitivity for detection of TICH irrespective of its location and volume was 93% (CI 88 - 96%). A study by Brogan et al. established the NIRS sensitivity of 78% computed after combining data from all studies published before 2017 [6]. The PPV of CEREBO® was 66% (60 - 72%). The reason for false positives, hence low PPV in our study was the presence of a hematoma in the adjacent lobe being scanned, thus reflecting mixed signals. The machine learning algorithm was made to reflect the result as positive even if there are mixed signals to improve the sensitivity. The CT scans were read at the axial section of the point of scanning by CEREBO® . If that corresponding axial section did not show hematoma, it was rated as negative for hematoma. The scanning with CEREBO® is performed at fixed points, however, there may be areas captured by the device beyond the point of scanning. The false positivity of the CEREBO® test for a given site (lobe) was due to the detection of a signal suggestive of hematoma beyond the scanned area.

The NPV of CEREBO® was 98% (CI 97 - 99%). An NPV of >95% is considered acceptable [6]. The combined NPV of 90% was reported in earlier studies [6]. The best NPV of 97% was obtained by Francis et al.'s device [11]. We had 13 false negative sites in our study. The type of the hematoma and a smaller bleed volume attributed to not being identified by CEREBO® in these cases. Six of these were SAHs and four ICHs were less ≤2 cc in volume. There were

Table 4
Performance of CEREBO® according to hematoma location.

	Overall $n = 944$	Frontal $n = 268$	Temporal $n = 316$	Parietal $n = 224$	Occipital $n = 136$
Sensitivity	93 (88 - 96%)	93 (82 - 98%)	94 (85 - 98%)	90 (76 - 97%)	100 (66 - 100%)
Specificity	90 (87 - 92%)	90 (85 - 94%)	91 (87 - 94%)	86 (81 - 91%)	90 (83 - 94%)
Accuracy	90 (88 - 92%)	91 (87 - 94%)	92 (88 - 95%)	87 (82 - 91%)	90 (84 - 95%)
PPV	66 (61 - 73%)	71 (59 - 81%)	74 (63 - 83%)	59 (46 - 71%)	41 (21 - 64%)
NPV	98 (97 - 99%)	98 (95 - 99%)	98 (96 - 100%)	98 (94 - 99%)	100 (97 - 100%)
PLR	8.9 (7.80 - 10.96)	9.4 (2.20 - 4.59)	10.7 (7.13 - 15.98)	6.6 (4.54 - 9.67)	9.8 (5.84 - 16.35)
NLR	0.08 (0.05 - 0.14)	0.08 0.04 - 0.27)	0.07 (0.03 - 0.17)	0.12 (0.05 - 0.29)	0.00

PPV – positive predictive value.
NPV – negative predictive value.
PLR - positive likelihood ratio.
NLR - negative likelihood ratio,.
Sensitivity specificity and accuracy are in percentages. The numbers in the bracket give the 95% confidence interval calculated using the Clopper-Pearson exact method.

Table 5
Performance of CEREBO® according to hematoma type.

	Subarachnoid n(cases) = 29 n(controls) = 774	Epidural n(cases) = 35 n(controls) = 774	Subdural n(cases) = 46 n(controls) = 774	Intracerebral n(cases) = 60 n(controls) = 774
Sensitivity	79% (60 - 92%)	100% (90 - 100%)	100% (92 - 100%)	90% (76 - 97%)
Specificity	90% (87 - 92%)	90% (87 - 92%)	90% (87 - 92%	90% (87 - 92%
Accuracy	89% (87 - 91%)	90% (88 - 92%)	90% (87 - 92%)	90% (87 - 92%)
PPV	22% (15 - 31%)	30% (22 - 39%)	36% (28 - 45%)	40% (32 - 49%)
NPV	99% (98 - 100%)	100% (99 - 100%)	100% (99 - 100%)	99% (98 - 100%)
PLR	7.58 (5.74 - 10.00)	9.56 (7.78 - 11.74)	9.56 (7.78 - 11.74)	8.60 (6.88 - 10.74)
NLR	0.23 (0.11 - 0.47)	0.00	0.00	0.11 (0.05 - 0.24)

PPV – positive predictive value.
NPV – negative predictive value.
PLR - positive likelihood ratio.
NLR - negative likelihood ratio.
The numbers in the bracket give the 95% confidence interval calculated using the Clopper-Pearson exact method.

Table 6
Performance of CEREBO® according to hematoma volume.

	Volume <2 ml n(cases) = 55 n(controls) = 774	Volume ≥2 ml n(cases) = 115 n(controls) = 774
Sensitivity	84% (71 - 92%)	97% (93 - 99%)
Specificity	90% (87 - 92%)	90% (87 - 92%)
Accuracy	89% (87 - 91%)	91% (88 - 92%)
PPV	36% (28 - 45%)	58% (51 - 65%)
NPV	99% (98 - 99%)	100% (99 - 100%)
PLR	7.99 (6.31 - 10.13)	9.31 (7.56 - 11.46)
NLR	0.18 (0.10 - 0.33)	0.03 (0.01 - 0.09)

PPV – positive predictive value.
NPV – Negative Predictive Value.
PLR - positive likelihood ratio.
NLR - negative likelihood ratio.
The numbers in the bracket give the 95% confidence interval calculated using the Clopper-Pearson exact method.

Table 7
Cases missed by CEREBO® scanning.

Patient No.	CT Details					Probable reasons
	Location	Type of Hematoma	OD	Depth (cm)	Volume (cc)	
14	Temporal	Subarachnoid	0.048	0.7	–	–
16	Frontal	Intracerebral	0.042	0.4	12.7	Hematoma was basifrontal
30	Frontal	Intracerebral	0.011	3.5	0.33	Volume ≤2 cc
	Temporal	Intracerebral	0.011	3.4	0.26	Volume ≤2 cc
76	Frontal	Subarachnoid	0.038	0.5	–	–
80	Temporal	Intracerebral	0.086	0.8	21	Mixed density contusion, largely hypodense
114	Frontal	Subarachnoid	0.089	0.7	–	–
134	Parietal	Intracerebral	0.062	0.7	13.3	Major portion of hematoma was below parietal point of scanning. The temporal portion of hematoma was detected in this case.
136	Parietal	Subarachnoid	0.041	0.8	–	–
148	Parietal	Subarachnoid	0.091	0.8	–	–
155	Temporal	Subarachnoid	0.054	0.5	–	–
	Temporal	Intracerebral	0.054	0.5	2	Volume ≤2 cc
194	Parietal	Intracerebral	0.045	2.1	0.5	Volume ≤2 cc

CT- computed tomography.
ODR – optical density ratio.

three cases of ICH more >10 cc in volume. The first was in the basifrontal region, which was inferior to the frontal point of scanning by CEREBO® . The second had mixed hypo and hyperdense contusion, and the volume of the hyperdense component, which was not calculated separately, was small. The third was the parietal component of large temporoparietal ICH. In this case, the temporal portion was detected but the parietal was missed. The sensitivity of NIRS devices depends on a number of factors like timing of scanning, the volume of hematoma, location of hematoma, depth of hematoma and type of hematoma. In our present study, we performed CT scans and NIRS consecutively at the same time in the emergency room. The TICHs evolve, and may be absent at the time of early NIRS scanning and detected later with a CT scan. Small TICHs may not be detected with NIRS. The CEREBO® detected hematomas as small as 1.6 cc. The sensitivity improves with an increase in the volume of TICH. In our present study the sensitivity for detecting TICH >2 cc was 97% (CI 93 - 99%) compared to 84% (CI 71 - 92%) with smaller hematomas. The volume

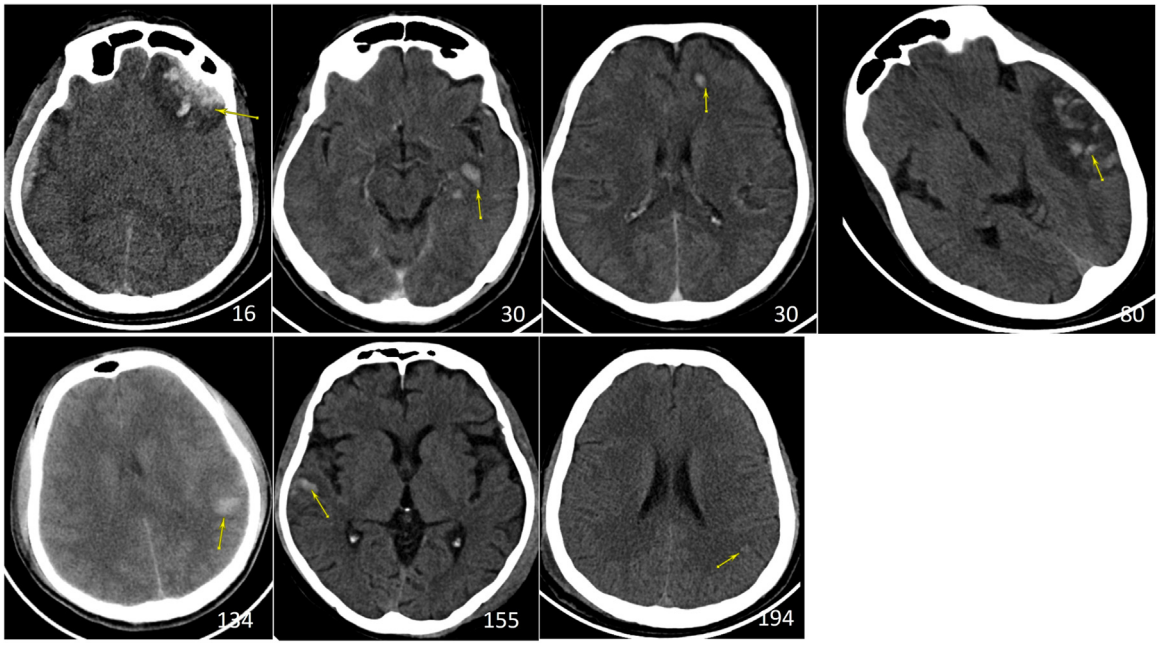

Fig. 6. CT scan findings of locations of hematomas missed by NIRS device. The number indicates the chronological number of patients.

of hematoma is used as an indication for surgery. The BTF guidelines recommend surgery for evacuation of EDH >30 cc in supratentorial location and contusion/ ICH> 50 cc. The combined sensitivity of 96% was obtained in detecting TICHs requiring emergency evacuation in reported studies [5]. Nine patients required surgery in our patient cohort and all were detected with CEREBO® . The commonest sites of TICH are frontal and temporal. In our study, the sensitivity for detecting frontal and temporal hematomas was 93% (CI 82 - 98%) and 94% (CI 85 - 98%) respectively. Other studies have not reported separately the sensitivity based on the location of the hematoma.

Deeper lesions can be missed with NIRS scanners as the infrared light may not penetrate deep enough [12]. The deepest hematoma in our present study was 2.8 cm from the outer table of the skull. Other studies have reported depth from the brain surface. [6] We chose the outer table of the skull as the thickness of the skull varies. Besides the thickness of the skull, any factors that can alter the path of light may affect the accuracy of the detection of hematoma. These include hair type, skin pigment, and subgaleal hematomas. Due to the mechanisms of injury resulting in an open cut/ lacerated scalp wound a large proportion of patients may not be suitable for NIRS examination. In our present study 324 out of 1264 (25.6%) sites were not available for scanning because of scalp lacerations. Among all the TICHs, EDH and SDH require urgent surgical evacuation. The sensitivity of detecting EDH and SDH was 100% in our present study. With other devices as well the rates of detection of EDHs and SDHs requiring surgeries have been excellent [6]. The sensitivity of detecting SAH was the least at 79%. The traumatic SAHs are thin and in the depth of the sulcus making them difficult to detect. However, traumatic SAH does not require any specific treatment in the acute setting.

A total of 32 bilateral hemorrhagic lobes were found in this study. The sensitivity to detect bilateral hemorrhages was 94% (CI 74 - 99%). Two bilateral hemorrhages could not be detected by CEREBO®, one was a subarachnoid hemorrhage of unknown volume present in the parietal lobe and the other was an intracerebral hemorrhage present in the right as well as the left temporal lobe. However, the volumetric difference between the two hemorrhages was less than 2 ml.

Limitations

There are certain limitations to the study and to the NIRS device itself. The presence of bilateral TICH would only be detected with NIRS if the volumetric difference is greater than 2cc, since the technique measures the difference in optical density between the hemispheres. In the case of bilateral hematomas with a smaller volumetric difference or no difference at all (symmetrical bilateral hematomas), no difference in optical density will be detected. Thus, it might lead to false results. However, symmetrical hematomas are very rare [13].

There can be an error due to skin color and the presence of hair color. The occipital sites need to be carefully examined in patients suspected to have a spinal injury. The occipital site scanning may be deferred pending spine clearance. As the commonest sites of traumatic ICH are frontal and temporal most of the hematomas can still be detected. This study has some other limitations too. As the algorithm is set to detect the hematomas in fixed locations, bleeding in other intracranial compartments cannot be detected e.g. interhemispheric SDH and posterior fossa hematomas. The depth of the ICH may be a limiting factor. The deeper hematomas like intraventricular hemorrhage, basal ganglia hemorrhage, corpus callosum bleeding, brainstem hemorrhage, etc. which are found in diffuse axonal injuries are not detected. Anyway, such patients with diffuse injuries are unconscious and require a CT scan. The NIRS scanning can rule out TICH requiring surgical evacuation in unconscious patients. The NIRS is not indicated to replace CT scans but complements the indications for CT scans after head injury. The subgaleal hematomas can give false positive alarms. The presence of lacerations of the scalp may render some locations inaccessible, which can be a significant proportion as scalp lacerations are common in head injuries following road traffic accidents. Assessment of atleast two lobes was possible in all patients, however, assessment of all eight lobes was possible in only 54 out of 158 patients. Because of scalp lacerations nearly 34% sites were inaccessible.

Conclusion

The currently tested NIRS device CEREBO® performed well as compared to other studies using other devices. The overall sensi-

tivity, specificity, and accuracy were 90% or more. The NPV was 97%, which was more than the acceptable cutoff of 95%. The sensitivity for detecting EDH and SDH was 100% and for detection of any type of hematoma >2 cc was 90%. These figures indicate that the current NIRS device can be used for screening and triaging patients when a CT scan is not available. This NIRS device can complement clinical prediction rules for indication of CT scan following head injury. The NIRS is not a diagnostic tool. It cannot replace a CT scan. A CT scan of the head is required immediately if the NIRS scanning results are suggestive of intracranial hematoma. As the NIRS is harmless it can be performed repeatedly along with clinical examination in a patient with a head injury who is being observed. A highly sensitive but less specific screening tool can lead to secondary over triage. The number of sites needed to scan with CEREBO® was three to detect one site of hematoma on CT scan. As this number is not large this will not lead to over-triage. Since the NIRS device is battery-operated, it can be used as a bedside detection tool to generate results within 3–5 min. Although centered on the NIRS principle, the machine learning algorithm enhances the accuracy of the system by eliminating the effect of outliers. Also, the automatic data acquisition and processing makes the device very useful in remote locations where an expert may not be available for interpreting the results. In addition, the color-coded graphical interface makes it very easy for even a non-skilled staff to comprehend the result. Thus, the NIRS device can fasten the patient triage so that the patient can be transferred to an appropriate and equipped health center within the golden hour, particularly in resource-constrained settings. A negative result in absence of high-risk factors can help to rule out the need for the patient to undergo the CT scan whereas a positive result will help to prioritize the patients who need immediate medical attention.

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Author contributions

All authors contributed to the study's conception and design. Material preparation and analysis were performed by DS, SK, and BID. Data collection was performed by GP, RJ, BL, and MS. The first draft of the manuscript was written by DS and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Ethics declarations

This study was approved by NIMHANS Institute Ethics Committee No. NIMHANS/24TH ICE (BS & NS DIV.)/2021 dated September 1, 2020 and an informed consent was obtained from the next available kin of the patients.

The study was registered on ClinicalTrials.gov (NCT05189561) retrospectively.

Declaration of Competing Interest

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.injury.2023.03.014.

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