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Non-Invasive Intracranial Pressure Monitoring and Management: Algorithm-Based Applications in Resource-Constrained Settings

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ABSTRACT

Intracranial hypertension is a major cause of secondary brain injury and adverse outcome following severe traumatic brain injury and other acute neurological conditions. Invasive intracranial pressure (ICP) monitoring remains the reference standard, but its availability is inconsistent in low- and middle-income countries (LMICs). Non-invasive ICP (nICP) technologies, including optic nerve sheath diameter (ONSD) ultrasonography, transcranial Doppler (TCD), quantitative pupillometry and imaging-derived markers, offer potentially scalable alternatives. This narrative review summarizes the current evidence for clinically available nICP techniques and examines their integration into algorithm-based management in resource-constrained settings. Contemporary consensus recommendations, including the Brussels consensus for non-invasive ICP monitoring (B-ICONIC), and the Consensus REVised Imaging and Clinical Examination (CREVICE) and Seattle International Severe Traumatic Brain Injury Consensus Conference (SIBICC) treatment algorithms were considered. ONSD ultrasonography, TCD and quantitative pupillometry provide complementary information but cannot currently reproduce the continuous and direct measurement obtained with invasive ICP monitoring. ONSD has demonstrated moderate diagnostic accuracy for intracranial hypertension, whereas TCD-derived indices and quantitative pupillometry appear particularly useful for serial trend assessment. Their clinical value is greatest when integrated with neurological examination, physiological variables and neuroimaging rather than interpreted as isolated numerical surrogates of ICP. A tiered algorithm incorporating clinical assessment, nICP assessment, basic ICP-lowering measures, hyperosmolar therapy, repeat assessment and timely neurosurgical referral is proposed for LMIC settings. Algorithm-based implementation can facilitate early recognition of deterioration, standardize treatment escalation and improve the use of limited neurocritical care resources. Prospective validation of multimodal nICP algorithms in LMIC populations is urgently required.

Key words: *intracranial pressure, low- and middle-income countries, non-invasive monitoring, optic nerve sheath diameter, quantitative pupillometry, transcranial Doppler.*

INTRODUCTION

Intracranial hypertension (IH) is a major determinant of secondary brain injury and poor outcome following severe traumatic brain injury (TBI), intracranial hemorrhage, subarachnoid hemorrhage, hydrocephalus, central nervous system infection and other acute neurological disorders. The physiological consequences of raised intracranial pressure (ICP) include reduction in cerebral perfusion pressure (CPP), impairment of cerebral blood flow, brain tissue ischemia and, ultimately, cerebral herniation and death. Consequently, early recognition and treatment of intracranial hypertension are central components of neurocritical care. Traditionally, ICP monitoring has relied on invasive techniques, principally intraventricular catheters and intraparenchymal pressure probes. Although these remain the reference standard, their availability is highly variable, particularly in low- and middle-income countries (LMICs) or resource constrained settings, where cost, availability of equipment, neurosurgical expertise, infection-control requirements and limited intensive care resources may restrict their use.[1,2]

The Brain Trauma Foundation (BTF) recommends treatment of ICP above 22 mmHg in severe TBI, while a CPP target of 60 – 70 mmHg is generally recommended.[1] Importantly, however, monitoring alone does not improve outcome; the benefit arises from using monitoring information to guide timely and appropriate treatment. In resource-constrained environments, therefore, the challenge is not simply to identify a substitute for an invasive ICP monitor but to construct a multimodal, clinically integrated and algorithm-based strategy that allows early detection of deterioration and standardized escalation of treatment.

Recent developments in bedside ultrasonography, transcranial Doppler (TCD), quantitative pupillometry and imaging-derived markers have created opportunities for non-invasive intracranial pressure (nICP) assessment. The 2025 Brussels consensus on non-invasive ICP monitoring represents an important advance by specifically addressing how these technologies can be incorporated into clinical decision-making when invasive ICP monitoring is unavailable.[3]

The B-ICONIC (Brussels Consensus for Non-Invasive Intracranial Pressure Monitoring when Invasive Systems Are Not Available in the Care of TBI Patients) consensus was developed to address the substantial global inequity in access to invasive intracranial pressure (ICP) monitoring, particularly in low- and middle-income countries. Recognising that invasive ICP monitoring may be unavailable because of cost, infrastructure, expertise, or patient-related contraindications, the consensus aimed to provide a pragmatic framework for monitoring and managing intracranial hypertension using non-invasive ICP (nICP) techniques integrated with serial neurological examination and neuroimaging. A multidisciplinary international panel of 41 experts used a mixed-method approach incorporating three scoping reviews, four systematic reviews with meta-analysis, a modified Delphi process, and an in-person meeting with structured discussion and voting. The process generated 34 recommendations, including 32 strong and 2 weak recommendations, addressing the selection and interpretation of nICP modalities, their use in guiding ICP-directed therapy, and thresholds for treatment escalation and de-escalation. Four clinical escalation algorithms and de-escalation heatmaps were also developed. B-ICONIC was intended to provide a structured, resource-sensitive approach to TBI management when invasive ICP monitoring is not available, while acknowledging the need for further prospective validation of these recommendations in clinical practice.[3]

Why non-invasive ICP monitoring matters in resource-constrained settings

Invasive ICP monitoring requires specialized equipment, trained personnel, sterile insertion and maintenance, appropriate imaging and the capacity to manage complications such as hemorrhage, infection, malposition and device malfunction. These requirements can be difficult to fulfil outside high-resource neurocritical care units. In many hospitals in the LMICs, even when neurosurgical services are available, invasive ICP monitoring may not be consistently accessible. Recent global consensus work has highlighted substantial variability in neurocritical care infrastructure and monitoring capacity across LMICs.[4]

The absence of an ICP monitor, however, should not equate to an absence of structured neurological monitoring. Clinical examination, pupillary responses, serial imaging and physiological parameters can be integrated with relatively inexpensive bedside technologies. The CREVICE protocol was developed specifically to provide a consensus-based approach to severe TBI when ICP monitoring is not employed, particularly in resource-limited environments.[5] The CREVICE protocol was developed to provide a structured approach to the management of severe TBI when invasive ICP monitoring is unavailable. It was conceived in response to the substantial variation in TBI management across resource-limited settings, where access to ICP monitoring and advanced neuromonitoring is often constrained. CREVICE uses readily available clinical examination and neuroimaging (ICE: Imaging and Clinical Examination) to identify patients at risk of intracranial hypertension and guide treatment escalation. The protocol was developed through an international expert consensus process and provides tiered, algorithm-based recommendations for recognition and management of suspected intracranial hypertension, thereby offering a pragmatic alternative for settings in which guideline-based ICP-directed care cannot be implemented because invasive monitoring is unavailable.

The conceptual shift should therefore be from "non-invasive ICP monitoring as a replacement for invasive ICP monitoring" to "non-invasive multimodal assessment as a decision-support system." No currently available non-invasive technique provides a continuous, universally accurate measurement equivalent to an intraventricular or intraparenchymal ICP monitor.[6]

Available non-invasive methods

Optic nerve sheath diameter ultrasonography

Ultrasonographic measurement of the optic nerve sheath diameter (ONSD) is probably the most attractive bedside technique for resource-constrained environments. The optic nerve sheath is contiguous with the intracranial subarachnoid space; an increase in ICP is transmitted along the sheath and produces distension that can be visualized using ocular ultrasonography.

ONSD measurement is portable, relatively inexpensive, repeatable and does not expose the patient to radiation. Meta-analyses have demonstrated reasonable diagnostic performance. A 2023 meta-analysis of eight prospective studies involving 222 patients with TBI reported pooled sensitivity and specificity of approximately 82% each.[7] A subsequent systematic review including 548 adults and 120 children reported pooled sensitivity of 84% and specificity of 83%, with an optimal threshold around 5.76 mm in adults; however, substantial heterogeneity and risk of bias remained.[8]

ONSD should nevertheless not be interpreted as an absolute ICP measurement. Thresholds vary according to population, age, ethnicity, ultrasound technique, probe frequency, measurement plane and operator expertise. Ocular pathology may also interfere with interpretation. Thus, an increased ONSD should be regarded as evidence supporting suspected intracranial hypertension rather than a stand-alone indication for aggressive therapy.

Transcranial Doppler

TCD provides indirect information about cerebral hemodynamics. Changes in cerebral arterial flow velocities and pulsatility index may accompany alterations in intracranial pressure and cerebral perfusion. In transcranial Doppler (TCD), cerebral arterial blood-flow velocities provide an indirect assessment of cerebral hemodynamics and are commonly expressed as peak systolic velocity (PSV), end-diastolic velocity (EDV), and mean flow velocity (MFV). The pulsatility index (PI), calculated as (PSV – EDV)/MFV, reflects downstream cerebrovascular resistance and the interaction between cerebral perfusion pressure, vascular tone, and intracranial compliance. An increased PI, particularly when accompanied by a reduction in EDV, may suggest increased cerebrovascular resistance or reduced cerebral perfusion, including in the setting of raised ICP, although PI is not a direct measure of ICP and can be influenced by arterial blood pressure, $PaCO_2$, autoregulation, and vascular pathology. Trends in velocities and PI, rather than isolated values, are therefore generally more informative for bedside assessment. More sophisticated mathematical approaches, including the Czosnyka method, have been investigated to estimate ICP and CPP.

The principal advantage of TCD is that it can provide repeated bedside assessments without radiation or invasive instrumentation. Its disadvantages include dependence on an adequate acoustic window, operator expertise and uncertainty in translating Doppler-derived variables into absolute ICP values. Recent evidence suggests that estimated ICP may have a high negative predictive value but relatively poor positive predictive value, limiting its use as a stand-alone diagnostic test.[6]

TCD may therefore be particularly useful for *trend monitoring and risk stratification*, especially when combined with ONSD, pupillometry and clinical examination.

Quantitative pupillometry

The neurological examination remains fundamental in resource-constrained neurocritical care. However, manual assessment of pupil size and reactivity is subjective and affected by ambient light, examiner experience, sedation and pharmacological agents. Quantitative pupillometry provides objective measurements of pupil size, constriction velocity, latency and other parameters and generates indices such as the neurological pupil index.

A 2024 scoping review concluded that quantitative pupillometry has potential for early detection of neurological deterioration and intracranial hypertension, although evidence linking specific pupillometric indices to ICP remains insufficient to establish a universal ICP threshold.[9]

Quantitative pupillometry using dedicated automated devices may not be readily available in many resource-limited centres because of cost, infrastructure, and equipment constraints. Smartphone-based pupillometry represents a potential low-cost alternative, using the smartphone camera and dedicated applications to capture and quantify pupillary size and light reactivity. Such systems may provide objective measures such as pupil diameter, constriction velocity, and latency, thereby reducing inter-observer variability associated with conventional bedside examination. However, their accuracy and reproducibility can be affected by ambient illumination, camera characteristics, positioning, and software algorithms, and they should currently be regarded as an adjunct rather than a replacement for validated automated pupillometers or clinical neurological examination. Further prospective validation, particularly in resource-limited settings and in patients with acute brain injury, is required before widespread clinical adoption.

Computed tomography and other imaging markers

CT remains essential for identifying the structural cause of intracranial hypertension. Findings such as compressed basal cisterns, midline shift, ventricular compression, sulcal effacement, diffuse cerebral edema and herniation may support the diagnosis of intracranial hypertension. CT-based ONSD measurement and other quantitative imaging approaches have also been investigated.[10]

However, CT is intermittent rather than continuous and requires transportation of critically ill patients. In resource-constrained hospitals, access may be further limited by scanner availability, cost and transportation delays. Therefore, CT should complement rather than replace bedside monitoring.

An algorithm-based approach

The principal value of nICP monitoring in resource constrained settings lies in its integration into a predefined algorithm. Such an approach minimizes dependence on individual clinician judgment, reduces treatment delays and facilitates standardized escalation.

The B-ICONIC consensus provides the most directly relevant contemporary framework. Developed by an international panel of 41 experts, it produced 34 recommendations and four clinical algorithms for managing severe TBI using nICP techniques when invasive monitoring is unavailable.[3]

A practical resource-appropriate algorithm can be structured into five stages.

Stage 1: Identify patients at risk

Patients with severe TBI, deteriorating consciousness, abnormal CT findings, pupillary abnormalities, repeated vomiting, seizures, progressive neurological deficit or clinical evidence of herniation should be considered at risk of intracranial hypertension. The absence of an invasive monitor should never delay treatment in a patient with clinical evidence of herniation. Initial assessment of these patients should include variables shown in Table 1.

Table 1. Initial assessment of patients at risk of raised intracranial pressure

1.	Glasgow Coma Scale and serial neurological examination
2.	Pupil size, symmetry and reactivity
3.	Blood pressure and oxygen saturation
4.	Respiratory rate and ventilation
5.	Temperature
6.	Glucose
7.	Hemoglobin and relevant laboratory parameters
8.	Assessment of Computed Tomography findings
9.	Identification of hypotension, hypoxemia, hypercapnia and other secondary insults.

Stage 2: Establish baseline multimodal assessment

Where available, ONSD ultrasonography, TCD and quantitative pupillometry should be performed at baseline and repeated serially. The important principle is trend rather than a single measurement. This approach recognizes the limitations of individual tests and uses concordance between independent indicators to strengthen clinical decision-making.

Stage 3: Initiate basic ICP-lowering measures

The first-line management of suspected intracranial hypertension should consist of low-risk interventions. The head should be elevated approximately 30°, the head and neck maintained in a neutral position, venous obstruction avoided and painful or unnecessary stimulation minimized.[11] Oxygenation and ventilation should be optimized, fever treated and hypotension avoided. Analgesia and appropriate sedation may be required in mechanically ventilated patients. Hypotonic intravenous fluids should generally be avoided. Electrolyte abnormalities, particularly significant hyponatremia, should be corrected. These measures are inexpensive and should form the minimum standard of care, irrespective of whether nICP technology is available.

Stage 4: Escalate treatment according to multimodal evidence

When clinical or nICP evidence suggests significant intracranial hypertension, hyperosmolar therapy with mannitol or hypertonic saline may be considered. Both agents can reduce ICP, although their hemodynamic and metabolic profiles differ.[11,12] Hypertonic saline may be particularly attractive in patients in whom hypotension is a concern, whereas mannitol requires attention to volume status, renal function and serum osmolality.

A short period of controlled hyperventilation may be used as a temporary rescue intervention in impending herniation, but prolonged prophylactic hyperventilation should be avoided because cerebral vasoconstriction can worsen cerebral ischemia.[1,11]

If the patient fails initial medical treatment, urgent neurosurgical reassessment is required. CT should be reviewed for surgically treatable mass lesions, hydrocephalus or expanding hematoma. Where indicated, evacuation of a mass lesion, CSF diversion or decompressive surgery should not be delayed while attempting to obtain perfect nICP confirmation.

Stage 5: Reassess and de-escalate

A critical feature of an algorithm is not simply escalation but de-escalation. Following improvement in neurological examination, pupil reactivity, ONSD and/or TCD parameters, treatment should be reassessed and unnecessary interventions withdrawn progressively.

This is particularly important in LMICs, where prolonged sedation, mechanical ventilation, repeated osmotherapy and unnecessary ICU interventions consume scarce resources and may themselves produce complications.

Proposed practical algorithm for LMICs and resource constrained settings

A simplified bedside algorithm is summarized in Figure 1. This approach is consistent with the conceptual principles of CREVICE and B-ICONIC, while recognizing that treatment decisions should incorporate clinical and radiological context rather than rely on an isolated numerical nICP value.[3,5]

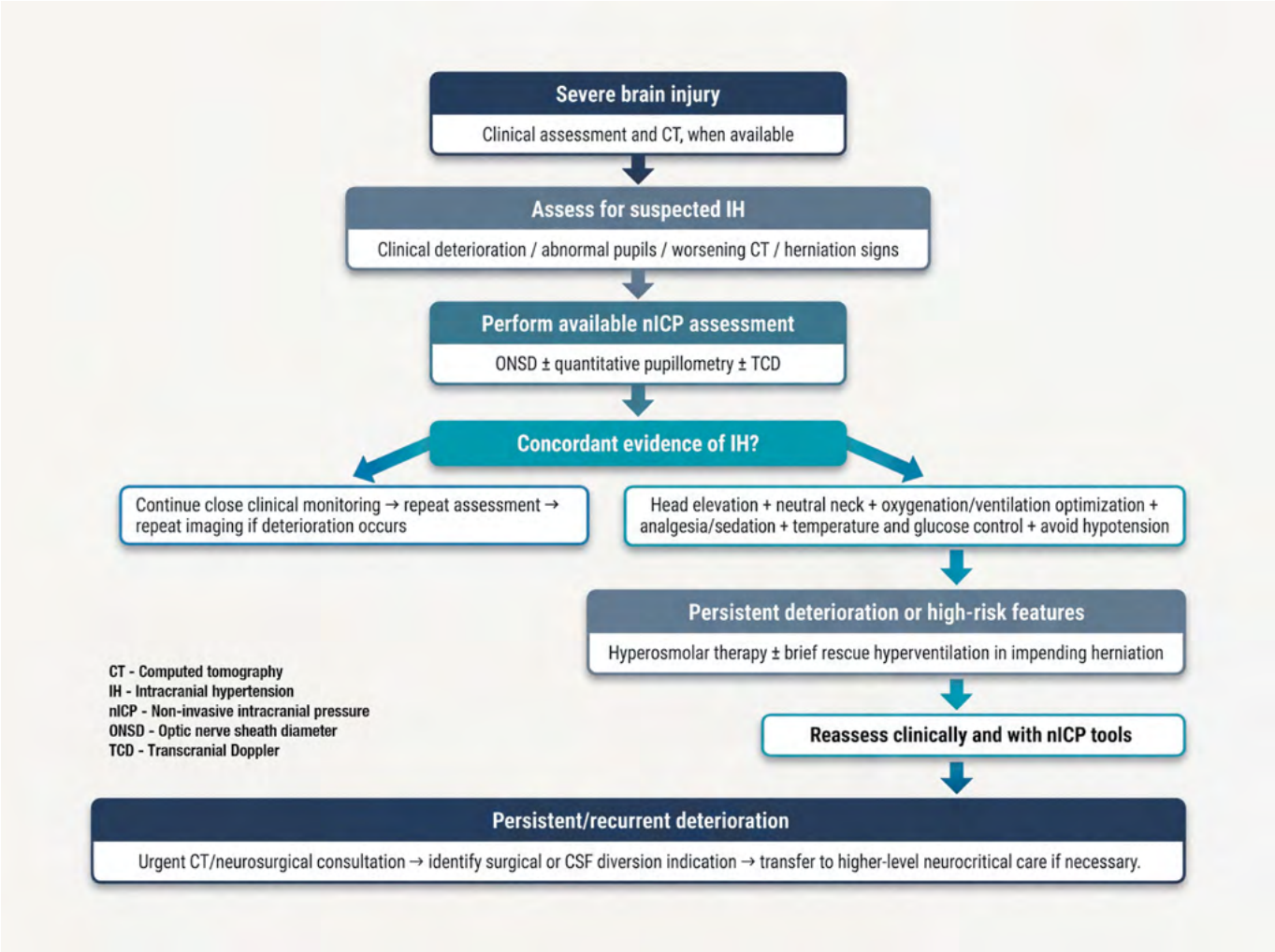


Figure 1. Algorithm for bedside management of patients with intracranial hypertension.

Implementation in resource-constrained environments

Successful implementation requires more than purchasing equipment. Training is likely to be the most important determinant of effectiveness. Ultrasound operators should receive standardized training in ocular ultrasound, including probe positioning, measurement technique, image quality assessment and recognition of confounding factors. TCD should similarly be performed by trained clinicians with competency in identifying appropriate vascular windows and interpreting flow patterns.

A tiered technology model may be especially appropriate. A basic center may use structured neurological examination and serial ONSD ultrasound. An intermediate center may add quantitative pupillometry and TCD. A tertiary neurocritical care center may combine these with invasive ICP monitoring, advanced imaging and multimodal neuromonitoring. Such an approach prevents the false dichotomy of "full neurocritical care versus no monitoring" and allows hospitals to progressively build capacity. Multiple factors need to be considered while managing these patients in places with resource limitations (Table 2).

Table 2. Factors to be considered for management of patients with intracranial hypertension in resource limited settings:

1. Which patients require non-invasive intracranial pressure assessment?
2. Which technologies are available locally?
3. How frequently should measurements be repeated?
4. What constitutes deterioration?
5. Which findings trigger treatment?
6. When should computed tomography be repeated?
7. When is neurosurgical consultation mandatory?
8. When should the patient be transferred to a higher-level center?

Limitations and future directions

Non-invasive ICP technologies have important limitations. None currently provides a universally reliable, continuous and absolute measurement of ICP. ONSD thresholds are heterogeneous; TCD-derived estimates depend on operator expertise and mathematical models; pupillometry can be

influenced by medications and ocular factors; and CT is intermittent and resource dependent.[6-10] Consequently, nICP should not be viewed as a replacement for invasive monitoring when the latter is available and clinically indicated. Rather, it should serve as a bridge between clinical examination and invasive neuromonitoring, particularly in settings where invasive monitoring cannot be delivered safely or consistently.

The Brain4Care (B4C) system represents an emerging technology for continuous, non-invasive assessment of intracranial compliance through detection of subtle cranial expansions associated with intracranial pressure pulsations. The system analyses intracranial pulse waveform morphology, particularly the P2/P1 ratio and time-to-peak (TTP), to identify changes in intracranial compliance and potential intracranial hypertension. Preliminary clinical studies have demonstrated encouraging diagnostic performance; however, variability in sensitivity and specificity, patient populations, and measurement protocols warrants further validation. Future iterations of this consensus may consider incorporating Brain4Care as an additional neuromonitoring modality, particularly in resource-constrained settings where invasive ICP monitoring is unavailable, following further evaluation of its diagnostic accuracy, clinical utility, feasibility, and cost-effectiveness.[13]

Future research should increasingly focus on the development and validation of multimodal, integrated algorithms rather than evaluating individual non-invasive monitoring devices in isolation. Intracranial hypertension is a dynamic physiological process, and no single non-invasive modality adequately captures the complex interactions between intracranial pressure, cerebral perfusion, cerebrovascular autoregulation, and intracranial compliance. Integration of optic nerve sheath diameter (ONSD), quantitative pupillometry, transcranial Doppler (TCD) parameters, systemic physiological variables (including blood pressure, heart rate, oxygenation, and respiratory parameters), and neuroimaging findings may provide a more comprehensive assessment of intracranial pathophysiology. Emerging machine-learning and artificial intelligence approaches could potentially identify complex patterns, temporal trends, and interactions among these variables to facilitate individualized risk stratification, early detection of neurological deterioration, and prediction of intracranial hypertension. Such models may also enable dynamic reassessment of risk and support clinical decision-making in settings where invasive ICP monitoring is unavailable. However, their development must incorporate adequately powered, prospective, multicentre validation, with assessment of calibration, discrimination, external generalizability, clinical utility, interpretability, and performance across different patient populations and resource settings. Importantly, algorithmic predictions should complement, rather than supersede, neurological examination, clinical judgement, and established diagnostic and therapeutic pathways. At present, the available evidence does not support replacing bedside clinical reasoning or invasive ICP monitoring, when indicated and available, with automated ICP prediction models. Their eventual clinical adoption should be guided by demonstrated improvements in patient-centred outcomes, feasibility, affordability, and equitable applicability across resource-variable healthcare systems.[14]

CONCLUSIONS

Non-invasive ICP monitoring offers an important opportunity to narrow neurocritical care disparities between high-resource and resource-constrained settings. ONSD ultrasonography, TCD, and quantitative pupillometry provide complementary information and should be integrated into a multimodal, trend-based, and algorithm-driven approach, rather than interpreted individually. The B-ICONIC framework provides a foundation for context-adapted management of severe TBI when invasive ICP monitoring is unavailable, emphasizing the integration of clinical examination, bedside technologies, neuroimaging, and standardized treatment pathways. Future progress will depend on the prospective validation of such integrated strategies to facilitate early recognition of intracranial hypertension, improve clinical decision-making, and potentially reduce secondary brain injury across LMICs.

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