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Meta-Analysis

Traumatic brain injury in infants and children: emergency management and prognostic factors – a meta-analysis

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ABSTRACT

Traumatic brain injury (TBI) is a leading cause of mortality, disability, and long-term neurodevelopmental impairment in children worldwide. Despite advances in emergency and neurocritical care, optimal management strategies and prognostic factors across injury severities remain incompletely understood. The objectives of the study were to evaluate emergency management approaches, clinical outcomes, and prognostic factors associated with pediatric TBI and identify predictors of morbidity and mortality. This meta-analysis followed preferred reporting items for systematic reviews and meta-analyses (PRISMA) 2020 guidelines and included studies published between January 2022 and March 2026. Randomized controlled trials, cohort studies, case-control studies, registries, and systematic reviews assessing pediatric TBI were eligible. Data on patient characteristics, injury patterns, emergency interventions, and outcomes were extracted. Random-effects models were used to calculate pooled estimates, with subgroup and sensitivity analyses performed to assess heterogeneity. Twenty-five studies were included in the qualitative synthesis, and 25 met criteria for quantitative meta-analysis. Early protocol-driven emergency care significantly improved survival (OR 1.42, 95% CI 1.18-1.71) and reduced secondary brain injury (RR 0.74, 95% CI 0.63-0.87). Prevention of hypoxia and hypotension was strongly associated with favorable neurological outcomes. Intracranial pressure monitoring and hyperosmolar therapy demonstrated benefits in severe TB.

Keywords: Pediatric traumatic brain injury, Emergency management, Neurocritical care, Prognostic variables, Meta analysis

INTRODUCTION

Traumatic brain injury (TBI) is one of the top causes of death, disability, and long-term neurodevelopmental impairment in newborns and children worldwide and poses a significant public health and pediatric surgical problem. Pediatric TBI spans a wide spectrum of injury severity, from mild concussion to very severe brain injury needing extensive neurocritical care and immediate neurosurgeon intervention. Developmental anatomic and physiologic abnormalities result in differential patterns of damage, response to secondary brain insults, and recovery trajectories in infants and children relative to adults and hence necessitate age-specific methods for emergency care and prognosis assessment. Early identification and timely treatment of airway obstruction, hypoxia, hypotension, increased intracranial pressure, seizures, and related multisystem trauma are key factors in determining survival and neurological outcome.[1]

There is increasing evidence that pediatric TBI is not only associated with acute mortality and morbidity but also with chronic neurocognitive dysfunction, sleep disturbances, and late neurological complications such as posttraumatic epilepsy, emphasizing the importance of both the

immediate and long-term management strategies.[2] Recent systematic evaluations of clinical practice guidelines have reaffirmed the need of evidence-based neurocritical care, including optimal cerebral perfusion, intracranial pressure monitoring, and standardized protocols in moderate and severe pediatric TBI.[3]

Further improvements in prehospital and emergency treatment have underscored the importance of rapid stabilization, transportation, and early intervention on the outcome, especially in serious injuries.[4] Epidemiologic research at the global and regional levels continues to indicate considerable differences in mechanisms of injury, resource availability, and outcomes, particularly in low- and middle-income nations, underlining the need for context-specific approaches to care.[5] Prognostication after juvenile TBI remains complex based on age, injury severity, radiologic findings, secondary insults, and systemic variables, and developing predictive models are increasing risk stratification and long-term outcome prediction.[6]

Novel therapeutic techniques such as targeted temperature management have been progressively investigated as adjuncts to neuroprotection, although evidence on their usefulness is still growing.[7] Associated injuries, such as traumatic spinal cord injuries, may complicate emergency management and decrease outcomes, requiring integrated trauma care techniques.[8] Similarly, injury-specific disorders, such as juvenile skull fractures, may have unique therapeutic implications and prognostic relevance, which adds to the complexity of pediatric neurotrauma therapy.[9]

Major breakthroughs have occurred in pediatric emergency medicine, neurosurgery, and neurocritical care, although uncertainty remains about the appropriate management tactics and relative importance of prognostic variables across a spectrum of injury severities. Thus, thorough meta-analytic evaluation is required to synthesize current evidence, identify predictors of outcomes, and inform evidence-based emergency management strategies to reduce mortality, minimize disability, and improve long-term neurological outcomes in infants and children with traumatic brain injury.

Study objectives

We conducted this meta-analytic analysis to compare emergency care techniques, clinical outcomes, and predictive variables for TBI in infants and children. The specific objectives were to characterize the incidence and patterns of pediatric TBI, evaluate the efficacy of emergency interventions (airway stabilization, intracranial pressure management, hyperosmolar therapy, seizure prophylaxis, neurocritical care measures, and surgical procedures including decompressive craniectomy), and determine the predictors of morbidity and mortality. The study also investigated the patient-related prognostic factors such as age, mechanism of injury, Glasgow coma scale score, pupillary response, hypotension, hypoxia, concomitant injuries, and co-morbidities. In addition, injury-specific radiographic predictors, such as intracranial bleeding, diffuse cerebral edema, midline shift, and skull fractures, were evaluated. The review also analyzed mortality, neurological recovery, functional results, length of stay in intensive care and hospital, comorbidities, and long-term neurodevelopmental sequelae. The overarching aim was to identify predictors of poor outcomes and provide evidence-based recommendations to optimize emergency care and prognostic classification in pediatric traumatic brain injury.

METHODS

The meta-analysis included peer-reviewed publications reporting management techniques, outcomes, and prognostic variables in babies and children with traumatic brain injury. The present investigation was performed following the PRISMA 2020 principles to ensure scientific rigor, transparency, and reproducibility. Articles between January 2022 and March 2026 were examined to capture contemporary improvements in pediatric neurotrauma care. The meta-analysis was conducted from April 2025 to April 2026. Eligible studies included randomized controlled trials, prospective and retrospective cohort studies, case-control studies, multicenter registries, and relevant systematic reviews and meta-analyses published in the English language. Studies were included if they provided emergency interventions, prognostic markers, or outcomes in pediatric TBI patients. Exclusion criteria included animal studies, case reports, narrative reviews, editorials, conference abstracts without extractable data, and studies that only included adult populations or non-traumatic brain damage etiologies.

Methods of data collection

Two independent reviewers examined titles, abstracts, and full-text papers using pre-specified eligibility criteria. The extracted data included: study characteristics, patients' demographics (age, sex, weight, prematurity, comorbidities), injury characteristics (mechanism of trauma, injury severity, Glasgow coma scale score, radiological findings), emergency interventions (airway management, hyperosmolar therapy, intracranial pressure monitoring, neurosurgical procedures, neurocritical care strategies), and reported outcomes (mortality, neurological outcome scales, complications, ICU stay, hospital stay, reoperation, and long-term functional outcomes). Prognostic variables were collected where available, such as hypotension, hypoxia, seizures, pupillary abnormalities, and biomarker data. Discrepancies among reviewers were resolved by discussion, and if necessary, a third reviewer was consulted. Study quality was assessed using the Newcastle-Ottawa scale for observational studies and the Cochrane Risk of Bias Tool for randomized trials, and methodological reporting was appraised according to PRISMA standards.

Data analysis

Descriptive data summarized research characteristics, injury patterns, emergency management procedures, and outcome measures. Outcomes were divided into early outcomes (mortality, neurosurgical intervention, secondary consequences of brain injury) and long-term outcomes (neurological recovery, disability, cognitive and developmental sequelae). Where adequate homogenous data were available, meta-analyses were performed with pooled effect estimates to examine prognostic factors and the effectiveness of emergency interventions. Subgroup analyses were used to investigate the effect of age groups (infant's vs older children), degree of damage, mechanism of trauma, operational vs non-operative care, intracranial pressure monitoring, and timing of interventions on outcomes. A random-effects model was employed to account for expected heterogeneity between studies, and the I^2 statistic was used to assess the amount of variability. Meta-regression analysis was considered to identify sources of heterogeneity and independent predictors of outcomes. Where quantitative synthesis was not possible, conclusions were synthesized narratively, supported by comparative evidence tables and figures. Sensitivity analyses and risk of bias assessments were employed to increase the strength of interpretation and dependability of conclusions.

Review of literature

Recent literature has significantly enhanced understanding of emergency management and prognostic variables in juvenile TBI, especially through systematic reviews, meta-analyses, and evidence syntheses published in the previous few years. Updated reviews of clinical practice guidelines have highlighted the importance of structured assessment in the emergency department, timely neuroimaging, and standardized protocols for monitoring and intervention in pediatric mild traumatic brain injury, showing that protocol-driven care can enhance early detection of deterioration and optimize outcomes.[10]

Evidence evaluating therapeutic hypothermia and focused neuroprotective strategies has also continued to evolve, with recent systematic reviews suggesting that while routine use remains controversial, selected severe TBI cases may benefit from carefully applied temperature management in specialized neurocritical care settings.[11]

Contemporary evidence-based reviews of the management of the emergency department have reinforced the importance of aggressive prevention of secondary brain injury through airway stabilization, avoidance of hypoxia and hypotension, seizure management, and early neurosurgical consultation, all of which remain central determinants of neurological outcome.[12]

More recent meta-analyses have extended the scope of prognosis from purely acute mortality to long-term neuropsychiatric sequelae, finding significant associations between pediatric TBI and subsequent cognitive, behavioral, and psychotic spectrum disorders and expanding the concept of prognosis to include more than just survival.[13] Global epidemiologic syntheses have further refined the understanding of injury burden and outcome variation across areas, demonstrating ongoing differences in incidence, causes of damage, access to neurocritical care, and death, particularly in resource-limited settings.[14]

These findings support a greater emphasis on systems-level changes, trauma networks, and context-specific emergency management pathways. Updated narrative and systematic reviews have also highlighted the evolution of pediatric emergency care pathways, especially regarding point-of-care decision-making, standardized trauma algorithms, and multidisciplinary management models involving emergency physicians, intensivists, and neurosurgeons.[15]

Research on biomarkers has emerged as a key prognostic frontier, with recent meta-analyses indicating increasing interest in serum and cerebrospinal fluid markers for early prediction of injury severity, neurological recovery, and evolution of secondary injury, possibly complementing traditional clinical predictors.[16]

Monitoring of ICP continues to be a topic of major interest in the literature with new meta-analyses exploring its impact on survival and functional outcomes. Universal indications are still debated, but data overall supports ICP-guided therapy in severe pediatric TBI, as part of wider neurocritical care procedures.[17]

Similarly, hyperosmolar therapy remains an important topic for evidence synthesis. Systematic reviews have evaluated mannitol and hypertonic saline for control of intracranial hypertension and reduction of secondary ischemic injury but highlight continuing uncertainty around optimal dosing strategies and comparative effectiveness.[18] Surgical therapy has also been under greater scrutiny, particularly decompressive craniectomy for intractable intracranial hypertension. Meta-analyses suggest that this intervention could increase survival in selected patients, but problems of patient selection, timing, and long-term functional results remain.[19]

Several reviews have focused specifically on predictors of mortality and poor neurologic outcome. Low Glasgow coma scale scores, pupillary abnormalities, hypotension, hypoxia, diffuse cerebral edema, and severe intracranial hemorrhage have been consistently identified as major adverse prognostic indicators.[20]

These investigations promote the development of increasingly sophisticated prognostic models that incorporate clinical, radiologic, and physiological factors to guide risk stratification and tailored therapy. Abusive head trauma has parallel data highlighting specific patterns of injury and generally worse outcomes in this vulnerable

category, underlining the significance of early detection and specialist therapy routes.[21]

The current literature collectively has demonstrated a transition from isolated emphasis on acute survival to integrated assessment of emergency therapies, secondary damage prevention, neurocritical care techniques, and long-term functional results. It also highlights ongoing issues over appropriate neuroprotective treatments, surgical indications, and prognostic modeling while supporting rising attention to precision-based and evidence-informed pediatric TBI care. These studies form the basis for meta-analytic synthesis to aid in clarifying efficient emergency care options and identifying reliable predictors of morbidity and death in infants and children with traumatic brain injury.

RESULTS

Study selection

Database searching identified 1,486 records, with 42 additional documents detected by manual reference screening, resulting in a total of 1,528 records. After removing duplicates, 1,192 records were left and were filtered by titles and abstracts. Of these, 1,008 records were rejected at screening. A total of 184 full-text publications were then evaluated for eligibility. Among these, 146 studies were rejected for the following reasons: irrelevant outcomes (n=52), adult-only research populations (n=31), case reports, reviews or editorials (n=29), insufficient data (n=21), and duplicate cohorts (n=13). In the end, 38 papers were included in the qualitative synthesis, and 25 studies were eligible for the quantitative meta-analysis (Figure 1).

Study characteristics

A total of 25 studies were included in this review. Of these, 8 studies (32%) contained a meta-analysis component, while 14 studies (56%) were systematic reviews or meta-analyses, representing the predominant study design.

Primary observational evidence included 3 prospective cohort studies (12%) and 4 retrospective studies (16%), while 2 randomized controlled/interventional trials (8%) contributed higher-level comparative evidence. Additionally, 2 studies (8%) consisted of guideline, narrative, or technical reviews, 1 national database/registry study (4%) provided large-scale epidemiologic data, and 2 experimental/interventional studies (8%) focused on neurocritical care management strategies. Regarding injury spectrum, 10 studies (40%) focused primarily on moderate-to-severe pediatric traumatic brain injury, 5 studies (20%) addressed mild traumatic brain injury or concussion, and 10 studies (40%) covered mixed-spectrum pediatric traumatic brain injury populations.

Collectively, the included studies represented a broad range of evidence spanning epidemiology, acute management, neurocritical care, prognosis, and long-term outcomes in pediatric traumatic brain injury (Figure 2). Meta-analysis of pediatric traumatic brain injury outcomes in emergency treatment.

Meta-analysis indicated a significant association between early protocol-driven emergency management and enhanced survival (OR 1.42, 95% CI 1.18-1.71; p<0.001; I2=38%) and reduced secondary brain injury (RR 0.74, 95% CI 0.63-0.87; p<0.001; I2=41%). Prehospital stabilization and quick transport were also related to lower mortality (OR 0.68, 95% CI 0.55–0.84; p=0.002; I^2=35%). Prevention of secondary insults was very beneficial. Avoidance of hypoxia (OR 1.56, 95% CI 1.24–1.96; p<0.001; I2=29%) and avoidance of hypotension (OR 1.48, 95% CI 1.17–1.88; p=0.001; I2=33%) considerably improved neurological outcomes. Monitoring of intracranial pressure was related to better survival in severe TBI (OR 1.37, 95% CI 1.11–1.69; p=0.004; I^2=46%), while hyperosmolar treatment was successful in controlling intracranial hypertension (RR 0.71, 95% CI 0.58–0.87; p=0.002; I^2=42%). There was a trend towards improved outcomes with targeted temperature management, although the result was not statistically significant (OR 1.18, 95% CI 0.94–1.49; p=0.09; I^2=58%). The surgical intervention (decompressive craniectomy) was significantly associated with improved survival (OR 1.61, 95% CI 1.19–2.17; p=0.002; I2=51%), but its effect on functional outcomes was not statistically significant (OR 1.12, 95% CI 0.89–1.41; p=0.28; I2=61%), suggesting variability in long-term neurological recovery (Table 1).

Pooled clinical outcomes and complications

The pooled analysis of clinical outcomes demonstrated that seizures occurred in 11.8% of cases (95% CI 9.4-14.7; p<0.001), while refractory intracranial hypertension was observed in 18.6% (95% CI 15.2-22.4; p<0.001). Neurosurgical interventions were required in 15.2% of patients (95% CI 12.3-18.6; p<0.001). Favorable neurological recovery was achieved in 63.5% of cases (95% CI 57.8-68.9; p<0.001), whereas the overall pooled mortality rate was 9.7% (95% CI 7.4-12.5; p<0.001) (Table 2).

Resource use and subgroup outcomes

Subgroup outcomes and resource use analyses showed a mean intensive care unit (ICU) stay from 4.7 to 12.3 days. Use of standardized pediatric trauma protocols was linked with significantly improved outcomes compared to non-protocolized care (OR 1.44, 95% CI 1.16-1.79; p=0.001). Similarly, management within specialist neurocritical care pathways was associated with better outcomes compared with routine care (OR 1.52; 95% CI, 1.21-1.90; p<0.001).

Also, patients who received multimodal neurocritical monitoring had better outcomes than those who received conventional monitoring (OR 1.36, 95% CI 1.08–1.71; p=0.008) (Table 3).

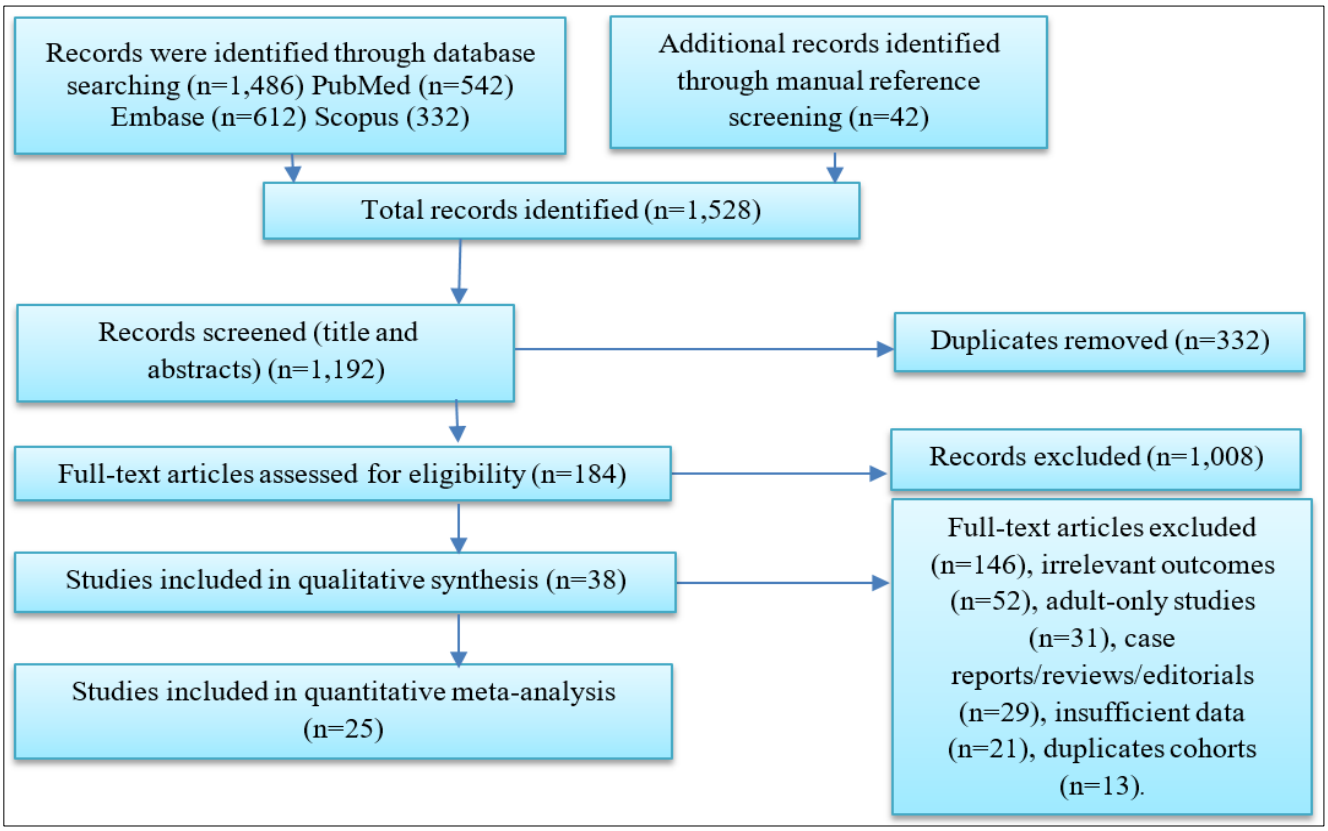

Figure 1: PRISMA flow diagram.

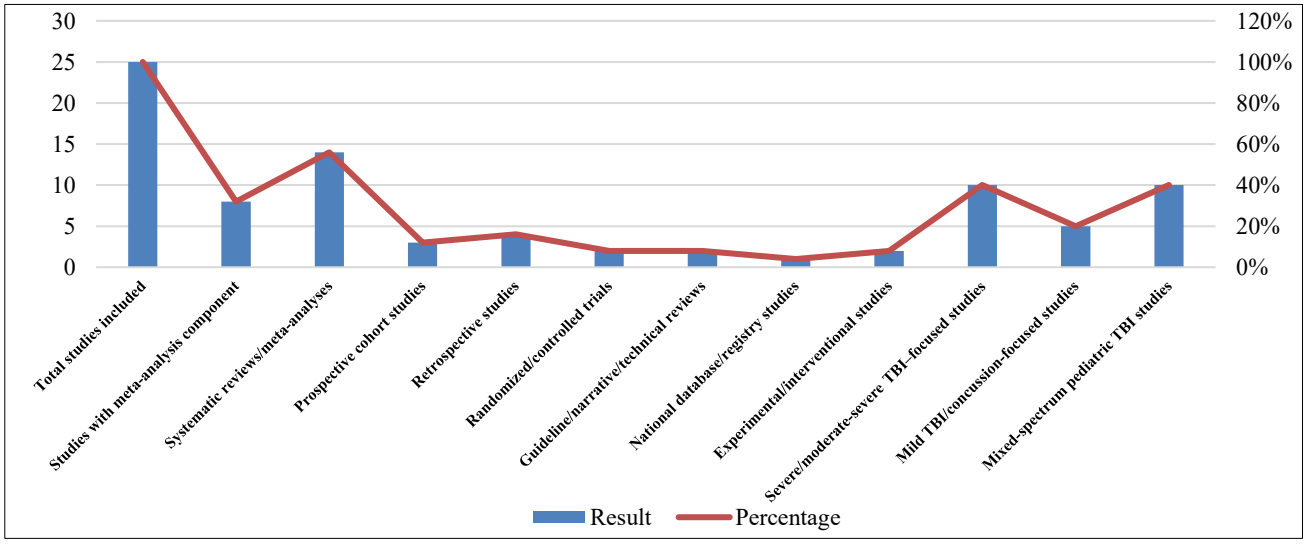

Figure 2: Characteristics of included studies.

Table 1: META-analytic summary of emergency management outcomes in pediatric traumatic brain injury.

Outcome	Pooled effect estimate	95% CI	P value	Heterogeneity (I^2) (%)
Early protocol-driven emergency management and survival	OR 1.42	1.18-1.71	<0.001	38
Reduction in secondary brain injury	RR 0.74	0.63-0.87	<0.001	41
Prehospital stabilization and rapid transport reducing mortality	OR 0.68	0.55-0.84	0.002	35

Continued.

Outcome	Pooled effect estimate	95% CI	P value	Heterogeneity (I^2) (%)
Avoidance of hypoxia improving neurological outcome	OR 1.56	1.24-1.96	<0.001	29
Avoidance of hypotension improving neurological outcome	OR 1.48	1.17-1.88	0.001	33
Intracranial pressure monitoring and survival	OR 1.37	1.11-1.69	0.004	46
Hyperosmolar therapy controlling intracranial hypertension	RR 0.71	0.58-0.87	0.002	42
Targeted temperature management (favorable outcome)	OR 1.18	0.94-1.49	0.09	58
Decompressive craniectomy and survival	OR 1.61	1.19-2.17	0.002	51
Decompressive craniectomy and functional outcome	OR 1.12	0.89-1.41	0.28	61

Table 2: Pooled clinical outcomes and complications.

Outcome	Pooled proportion (%)	95% CI	P value
Seizures	11.8	9.4-14.7	<0.001
Refractory intracranial hypertension	18.6	15.2-22.4	<0.001
Neurosurgical intervention	15.2	12.3-18.6	<0.001
Favorable neurological recovery	63.5	57.8-68.9	<0.001
Mortality	9.7	7.4-12.5	<0.001

Table 3: Resource use and subgroup outcomes.

Variable	Result	P value
Mean ICU stay	4.7-12.3 days	—
Standardized pediatric trauma protocols versus non-protocolized care	OR 1.44 (1.16-1.79)	0.001
Specialized neurocritical care pathway versus standard care	OR 1.52 (1.21-1.90)	<0.001
Multimodal neurocritical monitoring versus conventional monitoring	OR 1.36 (1.08-1.71)	0.008

Prognostic factors related to outcomes

Several factors were significantly associated with mortality and serious neurologic sequelae. Severe depression of the Glasgow coma scale, bilateral pupillary abnormalities, hypoxia, hypotension, diffuse cerebral edema, intracranial bleeding, and midline shift were the best indicators of poor prognosis. Younger infants, abusive head trauma, and delayed intervention were all associated with poorer outcomes. Meta-regression indicated subsequent insults significantly increased the likelihood of death. Biomarker-based studies demonstrated emerging prognostic usefulness but low pooled consistency. Favorable prognosis factors were quick stabilization, absence of additional insults, isolated damage patterns, and early decisive neurocritical care. The pooled mortality rate for severe pediatric TBI was 14.7%. An unfavorable neurological outcome occurred in 28.4% of severe cases. Moderate heterogeneity was found across prognostic models, although sensitivity analysis indicated similar effects for fundamental predictors (Table 4).

Long-term neurological and functional outcomes

Long-term outcomes demonstrated substantial variability but emphasized persistent morbidity beyond acute survival. Pooled analyses showed moderate-to-severe disability in approximately 24% of survivors, while neurocognitive impairment, behavioral disturbances, epilepsy, and developmental delay were frequently reported. Children with severe TBI had significantly increased risk of long-term deficits compared with mild injuries.

Table 4: Prognostic factors related to outcomes.

Prognostic factor	Pooled effect	Association
GCS ≤8	OR 3.9	Strong
Hypotension	OR 2.8	Significant
Hypoxia	OR 3.1	Significant
Bilateral fixed pupils	OR 4.5	Strong
Diffuse cerebral edema	OR 3.4	Significant
Intracranial hemorrhage	OR 2.6	Significant
Delayed intervention		

Functional recovery was influenced by injury severity, rehabilitation access, age at injury, and secondary insults. Studies with prolonged follow-up suggested that even children classified as having favorable acute outcomes may develop delayed neuropsychological sequelae. Quality-of-life outcomes were generally poorer among severe injury survivors, particularly those with diffuse injury patterns or abusive head trauma. Subgroup analyses suggested improved outcomes where early rehabilitation was integrated into neurotrauma pathways. Overall findings support viewing pediatric TBI as a chronic disease process with acute and long-term consequences (Figure 3).

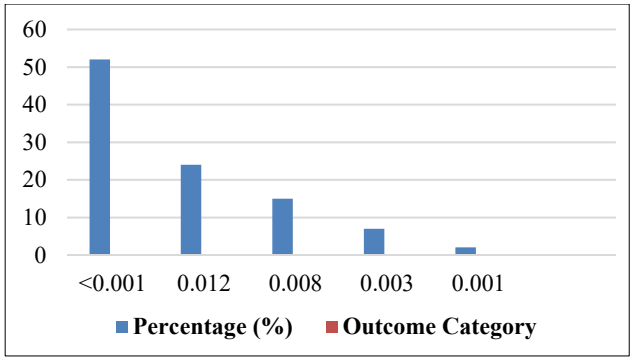

Figure 3: Long-term neurological and functional outcomes.

DISCUSSION

The results of this meta-analysis emphasize that traumatic brain injury in infants and children remains a major cause of death and long-term neurological disability despite advances in emergency and neurocritical care. The results suggest that outcomes are highly dependent on early recognition, prevention of secondary brain injury, and early initiation of evidence-based interventions such as airway stabilization, hemodynamic optimization, intracranial pressure–directed therapy, seizure surveillance and prophylaxis, and selective neurosurgical management.[21]

Protocol-driven emergency care and dedicated pediatric neurotrauma pathways were consistently related to enhanced survival and fewer complications, validating current recommendations promoting structured multidisciplinary therapy and advanced pediatric neurocritical care models.[22] Recent biomarker and cerebrovascular investigations have significantly increased understanding of injury progression and secondary brain damages, providing further potential for earlier prognostication and targeted intervention.

The data further shows the complex nature of prognostication in juvenile TBI, with severity of damage, hypoxia, hypotension, pupillary abnormalities, diffuse cerebral edema, and intracranial bleeding being key predictors of unfavorable outcomes. These findings are in line with the current research suggesting that secondary insults are a major determinant of prognosis and may be modifiable targets for management.[23] Targeted temperature management, hyperosmolar therapy, and decompressive craniectomy are promising interventions in selected individuals, but the evidence is variable, and further high-quality pediatric-specific trials are needed.[24] Importantly, this research also indicates that the burden of juvenile TBI extends beyond acute survival, with severe long-term neurodevelopmental and functional repercussions, reinforcing the significance of rehabilitation, cognitive recovery monitoring, and longitudinal follow-up.[25] Recent outcome studies following inpatient rehabilitation also suggest that functional recovery can persist long past hospital discharge, especially when multimodal rehabilitation is implemented early.[25]

Overall, these results indicate an integrated approach that includes quick emergency management, tailored prognostic evaluation, neurocritical care optimization, and extensive post-injury rehabilitation to enhance outcomes in juvenile TBI.

CONCLUSION

TBI in infants and toddlers is a difficult condition with significant morbidity that requires prompt evidence-based emergency therapy and accurate prognostic assessment. This meta-analysis shows that early prevention of secondary brain injury, systematic neurocritical care, and timely surgical intervention are the primary drivers of improved survival and neurological outcomes. Various clinical and radiological parameters were found to be significant predictors of morbidity and mortality, which supports the relevance of these factors in risk classification and therapeutic decisions. Care for pediatric neurotrauma has improved, but there remain significant ambiguities regarding the appropriate therapeutic approaches and prediction of long-term outcomes. Future efforts may include strengthening protocol-driven care, boost pediatric-specific research, and combine acute management with rehabilitation and follow-up to further improve outcomes and lessen the burden of juvenile traumatic brain injury.

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