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REVIEW

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# Effectiveness of controlled decompression against conventional decompression methods for the management of severe traumatic brain injury patients: a meta-analysis

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## Abstract

**Background** Severe traumatic brain injury (TBI) presents significant management challenges, with decompressive surgery being a critical intervention. This review aimed to evaluate the efficacy of controlled decompression versus conventional decompression techniques in managing severe TBI across multiple outcomes.

**Methods** A comprehensive search of electronic databases (PubMed Central, SCOPUS, EMBASE, Chinese national knowledge infrastructure, Cochrane trial registry, WHO trials platform) was conducted to identify studies comparing controlled decompression with conventional methods in severe TBI patients. Pooled analysis was done using a random-effects model with inverse variance technique.

**Results** Thirteen studies were included. Controlled decompression significantly reduced mortality (OR 0.498, 95% CI 0.321–0.773, $p=0.002$), postoperative complications (OR 0.283, 95%CI: 0.205–0.390, $p<0.0001$), cerebral infarction (OR 0.488, 95% CI 0.293–0.813, $p=0.006$), and brain swelling (OR 0.409, 95% CI 0.252–0.661, $p<0.0001$). Improvements were also observed in favorable outcomes (OR 1.822, 95% CI 1.211–2.740, $p=0.004$), prognosis (OR 2.488, 95%CI 1.292–4.792, p = 0.006), and total effective rate (OR 6.549, 95% CI 1.852–23.153, $p=0.004$). Minimal heterogeneities were found across outcomes, although the quality of evidence was downgraded to low due to higher risk of bias across most studies.

**Conclusions** Controlled decompression significantly improves outcomes in severe TBI patients compared to conventional methods. Future high-quality, multicenter randomized controlled trials are recommended to confirm these findings and guide clinical practice.

**Keywords** Controlled decompression, Meta-analysis, Traumatic brain injury

## Introduction

Severe traumatic brain injury (TBI) remains a prevalent cause of mortality and long-term disability worldwide, presenting substantial healthcare challenges and socioeconomic burdens [1] . The primary insult, which refers to the initial physical damage caused by the traumatic event, is often followed by secondary injury mechanisms, including brain swelling and the consequential rise in intracranial pressure (ICP) [2] .These secondary

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events can persist for days to weeks after the initial insult and contribute significantly to morbidity and mortality [2].

. As such, the management of TBI revolves not only around treating the primary injury but also mitigating these secondary injuries [3, 4]. The control of ICP is a cornerstone in the management of severe TBI, and various treatment modalities exist for this purpose [3, 4]. These range from medical interventions, such as osmotic therapy and sedation, to surgical procedures like decompressive craniectomy (DC) [2–4] . DC is a surgical method involving the removal of a portion of the skull to provide space for the swollen brain tissue, thus lowering ICP and hopefully minimizing secondary ischemic injury [5].

Despite its wide application, the timing, technique, and patient selection for DC are subjects of ongoing debate, underlining the need for comprehensive research and analysis [5] . One key area of interest is the distinction between conventional and controlled decompression methods [6] . Conventional DC, typically an immediate, large craniectomy, rapidly decreases ICP. However, it may also exacerbate brain herniation, cause subdural effusions, and lead to other complications [5] . In contrast, controlled or stepwise decompression aims to mitigate these risks by progressively enlarging the craniectomy over time [7, 8].

Historically, the literature contains a mixture of studies, with some supporting conventional decompression due to its immediate effectiveness in reducing ICP, while others advocate for the potential long-term benefits of controlled decompression [8–11] . However, no consensus exists on which method is superior, and the choice often relies on the individual surgeon's expertise and the specific patient's clinical scenario.

Given the critical role that decompression plays in managing severe TBI, it is imperative to determine the most effective and safest method of decompression. This manuscript aims to perform a review of the current literature comparing controlled and conventional decompression methods in the management of severe TBI. This review will provide a clearer picture of the relative merits and drawbacks of both methods, potentially guiding clinical decision-making and informing future research in this area. With an increased understanding of the pathophysiology of TBI and advancements in surgical techniques, the hope is that this meta-analysis will contribute to improved patient outcomes by informing best practice guidelines and stimulating further research on this critical topic. Hence, this study was done to compare the effectiveness of controlled depression technique against the conventional decompression for the management of severe traumatic brain injury patients.

## Methods

### Eligibility criteria

#### *Study design*

Eligible randomized controlled trials (RCTs) either parallel or cluster form were considered for inclusion. We incorporated full-text studies that met the eligibility criteria, while case reports/series and unpublished grey literature were excluded from the analysis.

#### *Study participants*

Studies were done amongst the adult patients (aged 18 years and above) undergoing treatment for severe TBI. Severe TBI was defined as a traumatic brain injury with a Glasgow Coma Scale (GCS) score of 3 to 8 on admission, indicating a critical reduction in consciousness and neurological functioning, necessitating immediate intervention to manage elevated intracranial pressure and other complications.

#### *Intervention and comparator groups*

Studies comparing the controlled or gradual decompression methods to conventional decompressive surgery for the release of ICP were considered.

#### *Outcomes*

Mortality, postoperative complications (overall, cerebral infarction, brain swelling, delayed hematoma), good prognosis, favourable Glasgow Outcome Scale (GOS) outcome, total effective rate.

In this review, favorable GOS outcome was defined as a score of 4 or 5, indicating moderate disability or good recovery, respectively, which reflects a satisfactory functional outcome following treatment.

Similarly, 'good prognosis' was defined as a clinical improvement with reduced severity of neurological deficits and an overall positive recovery trajectory as reported by the individual studies.

Total effective rate was defined as the proportion of patients showing clinical improvement based on a combination of parameters, including reduction in intracranial pressure, improved neurological function, and absence of significant complications. It represents the overall success rate of the intervention as reported by the included studies.

### Information sources and search strategy

The search was conducted in multiple databases, including PubMed Central, SCOPUS, EMBASE, Chinese databases such as Chinese National Knowledge Infrastructure (CNKI), Cochrane trial registry (CENTRAL), and WHO trials platform. Our search strategy incorporated medical subject headings (MeSH) and free-text terms. We employed appropriate Boolean operators ("AND," "OR,"

and "NOT") to combine predefined search terms. The search period spanned from January 1964 (or the inception of the database, whichever is earlier) to December 2023, without any language restrictions. The detailed search strategy utilized in the review is provided as **Supplementary File 1**.

### Selection process

A pair of independent researchers conducted the initial stage of the study selection process by examining the titles, keywords, and abstracts. Both investigators obtained full-text studies and narrowed them down for the second phase of screening according to the eligibility criteria. In the second step, the researchers evaluated the retrieved full-texts, and those that met the eligibility criteria were ultimately included for further analysis. The "Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) checklist 2020" was employed to report this review (**Supplementary File 2**) [12].

### Data collection process and data items

Upon determining the full-text articles eligible for inclusion, both researchers participated in the manual data extraction procedure, utilizing a predefined semi-structured data collection form. The following data were extracted: first author's name, publication year, study design, country of origin, sample size, patients' characteristics, decompression methods, patients outcomes, and adjustments for potential confounding factors.

### Study risk of bias assessment

Two researchers undertook the responsibility of assessing the included studies' quality. The Revised Cochrane risk-of-bias tool for randomized trials (RoB 2) was used for this purpose in RCTs [13] . The RoB 2 tool evaluates five areas: the process of randomization, discrepancies from the planned interventions, absence of outcome data, outcome measurement, and the choice of the reported outcome. Following this evaluation, every study was classified as having a low or high risk of bias or some concerns based on the findings. We have discussed any disagreements between the reviewers and come to a consensus, and if a consensus cannot be reached, we sought a third opinion.

### Effect measures and synthesis methods

By calculating the combined values of number of events and sample size in each group for dichotomous outcomes, the overall treatment effect was evaluated. The pooled analysis uses the random-effects inverse-variance model with the DerSimonian-Laird estimate. The results were presented in forest plots, with 95% confidence intervals (CIs) for individual study estimates and pooled effect sizes. Heterogeneity was assessed using the $I^2$ statistic, Cochran's Q test, and visual inspection of the forest plot [14] . STATA version 14.2 was used for the analysis.

We adopted the Grading of Recommendations Assessment, Development and Evaluation (GRADE) approach. This strategy focuses on assessing the quality of evidence through specific domains, including risk of bias, inconsistency, imprecision, indirectness, and publication bias [15] . However, we did not evaluate publication bias for fewer outcomes due to the limited number of studies (less than 10) [14] . Sensitivity analysis was performed by excluding high risk of bias studies to check the change in magnitude or direction of association.

## Results

### PRISMA flowchart interpretation

Across the databases, 3329 records were obtained, and after the duplicates removal (1289 duplicates removed), 2040 records underwent primary screening. Out of these records, 1909 were excluded at this stage itself, requiring the retrieval of full-texts of 131 articles. After retrieving these full-texts and applying the inclusion criteria, 13 studies were eligible and included in the analysis (Fig. 1) [8–11, 16–24].

### Characteristics of the included studies

This review encompassed 13 RCTs from China, focusing on patients with severe TBI, including those with complications. The studies, with sample sizes ranging from 50 to 248 participants, predominantly evaluated the efficacy of controlled decompression techniques against various conventional decompression methods. The interventions detailed varied in their approach to decompression, including controlled step decompression and controlled staircase decompression, compared to standard large bone flap decompression and decompressive craniectomy (Table 1). Among these studies, the risk of bias was considered high in 8 studies and some concerns were noted in the remaining 4 studies, indicating a need for cautious interpretation of the findings (Fig. 2).

### Mortality

This meta-analysis evaluated the effectiveness of controlled decompression versus conventional decompression methods in managing severe traumatic brain injury patients. It included five studies with a total of 651 participants. yielded an overall odds ratio of 0.498 (95% CI 0.321 to 0.773, $p=0.002$), indicating a significant benefit of controlled decompression in reducing mortality (Fig. 3). Heterogeneity across the studies was absent, with Cochran's Q value of 1.50 ($p=0.827$), H statistic of 0.612, and an $I^2$ of 0.0%, suggesting consistent findings among the included studies. Sensitivity analysis excluding high

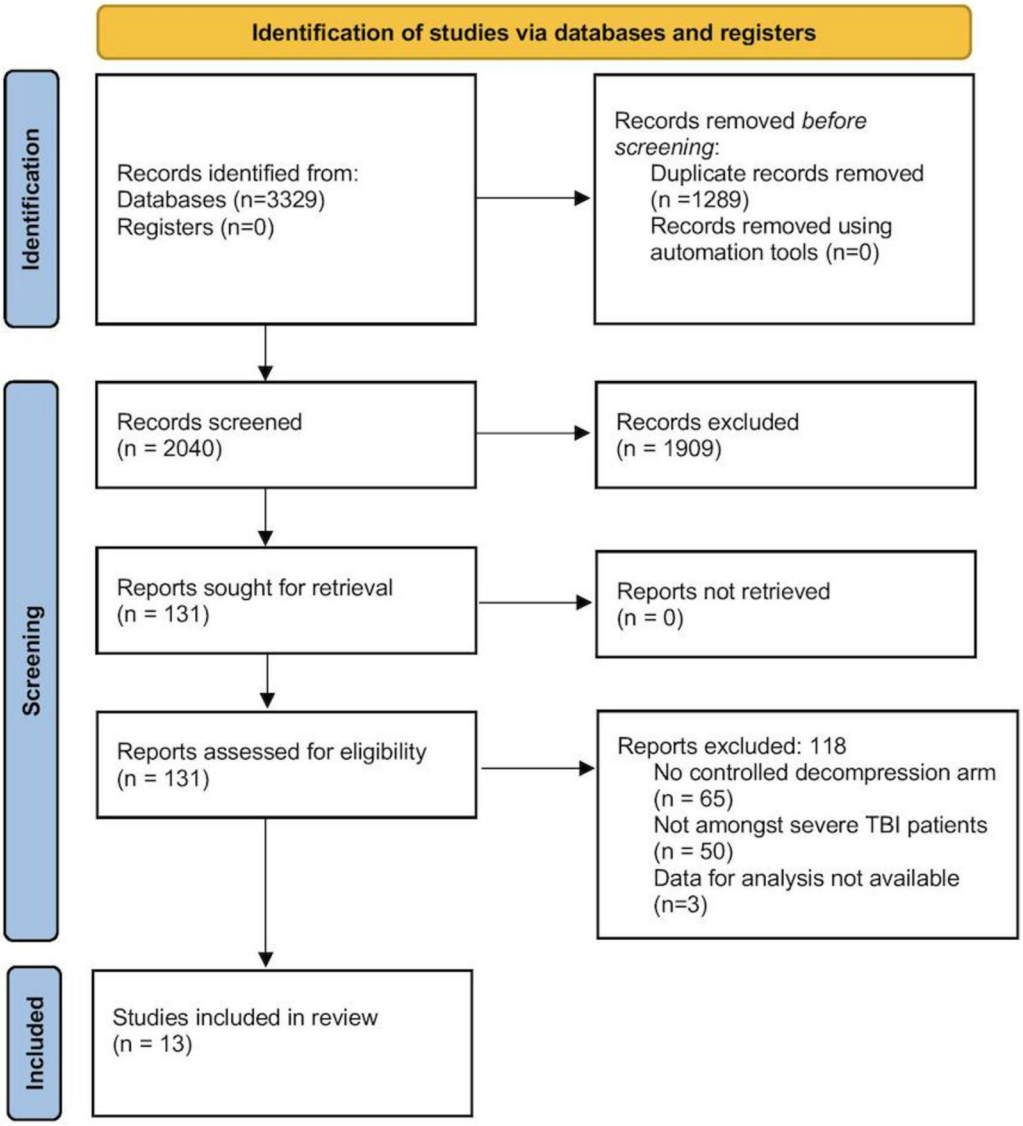


**Fig. 1** PRISMA flowchart

risk of bias studies did not show significant difference in the pooled estimate (pooled OR = 0.52; 95%CI 0.33 to 0.83; $n = 3$).

#### Postoperative complications (overall)

In this meta-analysis, which assessed the impact of controlled decompression compared to conventional methods on postoperative complications in severe traumatic brain injury patients, nine studies involving 965 participants were analyzed. The pooled odds ratio, using a random-effects model, was 0.283 (95% CI 0.205 to 0.390, $p < 0.0001$), indicating a significant reduction in postoperative complications with controlled decompression (Fig. 4). The heterogeneity among the studies was absent, with Cochran's Q statistic of 5.10 ($p = 0.747$), an H statistic of 0.798, and an $I^2$ of 0.0%, suggesting a consistent effect across the included studies. Sensitivity analysis excluding high risk of bias studies did not show significant difference in the pooled estimate (pooled OR = 0.28; 95%CI 0.19 to 0.42; $n = 4$).

#### Cerebral infarction

This meta-analysis evaluated the effect of controlled decompression versus conventional decompression methods on the incidence of cerebral infarction in patients with severe traumatic brain injury, including six studies with 630 participants. The analysis, utilizing a random-effects inverse-variance model, revealed

**Table 1** Characteristics of the included studies (N = 13)

| Author and year of publication | Country | Study design | Sample size | Study participants details | Intervention details | Comparator group details | Mean age (in years) | Glasgow coma scale | Duration of follow up |
|---|---|---|---|---|---|---|---|---|---|
| Liang et al. [17] | China | RCT | 80 | Elderly patients with severe craniocerebral injury complicated with cerebral infraction | Controlled decompression | Standard large bone flap decompression | NR | All patients had GCS less than 8 | 3 months |
| Sun et al. [18] | China | RCT | 100 | Patients with severe traumatic brain injury | Controlled decompression | Clinical craniotomy for hematoma removal and craniotomy decompression | I = 21.9 ± 1.2<br>C = 30.2 ± 1.4 | All patients had GCS less than 8 | 6 months |
| Tan et al. [19] | China | RCT | 150 | Patients with severe craniocerebral trauma | Controlled stepped decompression surgery | Standard large bone craniotomy | NR | All patients had GCS less than 8 | 6 months |
| Wang et al. [9] | China | RCT | 128 | Patients with severe head injuries with GCS score between 3 to 8 | Controlled decompression which comprises of controlled ventricular drainage and controlled hematoma evacuation | Conventional decompressive craniectomy | I = 44.2 ± 14.2<br>C = 41.8 ± 13.9 | Mean GCS in Intervention = 5.4; Control group = 4.8 | 6 months |
| Yuan et al. [24] | China | RCT | 50 | Patients with severe head injury | Controlled decompression | Conventional craniotomy and decompressive craniotomy | NR | All patients had GCS less than 8 | 6 months |
| Chen et al. [8] | China | RCT | 248 | sTBI patients aged 18–75 years old and e if an indication for DC existed | Intraoperative controlled decompression | Intraoperative rapid decompression | I = 48.0 ± 13.5<br>C = 50.3 ± 14.6 | 3–5: 91 patients<br>6–8: 157 patients | 6 months |
| Jia et al. [11] | China | RCT | 84 | Patients with severe craniocerebral injury | Controlled step decompression | Standard large decompressive craniectomy | NR | All patients had GCS less than 8 | 6 months |
| Jiao et al.[16] | China | RCT | 100 | Patients with severe craniocerebral injury | Controlled decompression | Standard large decompressive craniectomy | NR | All patients had GCS less than 8 | 6 months |
| Hu et al. [10] | China | RCT | 60 | Elderly patients with severe traumatic brain injury | Controlled decompression | Standard large trauma reduction buckling surgery | NR | All patients had GCS less than 8 | 6 months |
| Yang et al. [22] | China | RCT | 92 | Patients with severe craniocerebral injury | Controlled decompression surgery | Standard decompressive craniectomy treatment | NR | All patients had GCS less than 8 | 6 months |

**Table 1** (continued)

| Author and year of publication | Country | Study design | Sample size | Study participants details | Intervention details | Comparator group details | Mean age (in years) | Glasgow coma scale | Duration of follow up |
|---|---|---|---|---|---|---|---|---|---|
| Ye et al. [23] | China | RCT | 64 | Patients with severe craniocerebral injury treated in hospital during period of June 2020 to July 2022 | Controlled stepwise intracranial decompression | Control group is treated with conventional decompression surgery | NR | All patients had GCS less than 8 | 6 months |
| Wang et al. [20] | China | RCT | 159 | Patient with severe traumatic brain injury | Controlled staircase decompression | Treated with decompressive craniectomy | NR | All patients had GCS less than 8 | 3, 6 and 12 months |
| Xu et al. [21] | China | RCT | 80 | Patient with severe craniocerebral injury | Controlled stepwise decompression expression | Standard large bone flap decompression | NR | All patients had GCS less than 8 | 6 months |

GCS: Glasgow Coma Scale; I: Intervention group; C: Comparator group; NR: Not reported; RCT: Randomized controlled trial; sTBI: severe Traumatic Brain Injury; USA: United States of America

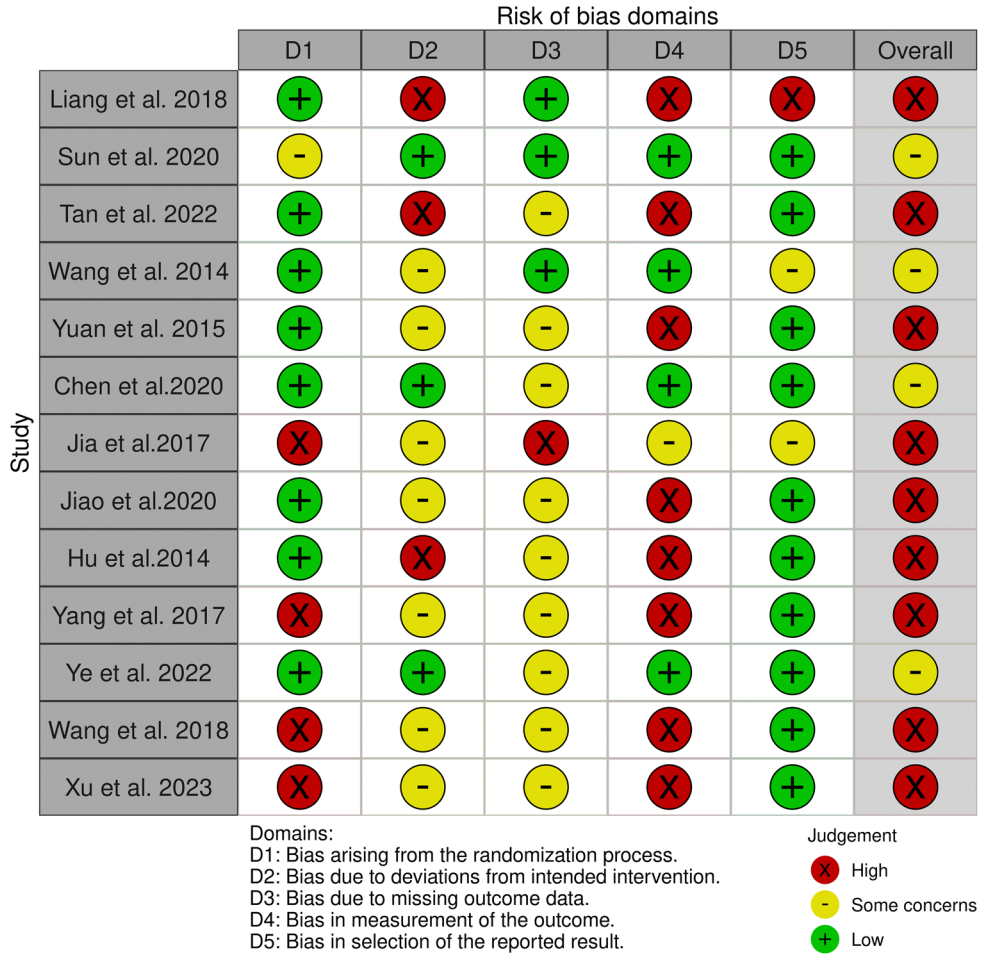


**Fig. 2** Forest plot comparing the effectiveness of controlled depression against conventional depression for mortality amongst severe traumatic brain injury patients

an overall odds ratio of 0.488 (95% CI 0.293 to 0.813, $p=0.006$), suggesting a significant reduction in the risk of cerebral infarction with controlled decompression (Fig. 5). Heterogeneity was minimal, with a Cochran's Q statistic of 5.91 ($p=0.315$), an H statistic of 1.087, and an $I^2$ of 15.4%, indicating relatively consistent results across the studies. Sensitivity analysis excluding high risk of bias studies showed that the impact of intervention on cerebral infarction becomes non-significant (pooled OR = 0.49; 95%CI 0.34 to 1.03; $n=2$).

### Brain swelling

In this meta-analysis investigating the impact of controlled decompression on brain swelling in patients with severe traumatic brain injury, four studies encompassing 458 participants were included. The pooled odds ratio, derived from a random-effects inverse-variance model, was 0.409 (95% CI 0.252 to 0.661, $p<0.0001$), indicating a significant reduction in the risk of brain swelling with the use of controlled decompression (Fig. 6). Heterogeneity among the studies was absent, with a Cochran's Q statistic of 0.88 ($p=0.830$), an H statistic of 0.543, and an $I^2$ of 0.0%, suggesting high consistency in the study findings. Sensitivity analysis excluding high risk of bias studies did not show significant difference in the pooled estimate (pooled OR = 0.40; 95% CI 0.23 to 0.71, $n=2$).

### Delayed hematoma

This meta-analysis evaluated the effect of controlled decompression on the occurrence of delayed hematoma in patients with severe traumatic brain injury, including three studies with a total of 398 participants. The pooled odds ratio, calculated using a random-effects inverse-variance model, was 0.534 (95% CI 0.334 to 0.854, p = 0.009), indicating a significant reduction in the risk of delayed hematoma with controlled decompression (Fig. 7). The heterogeneity among the included

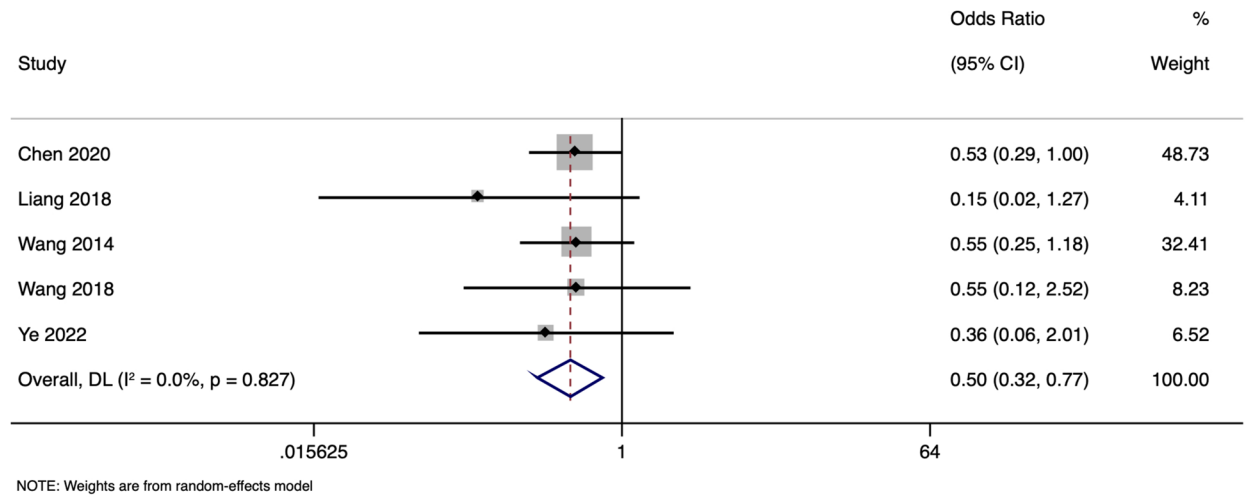


**Fig. 3** Forest plot comparing the effectiveness of controlled depression against conventional depression for overall postoperative complications amongst severe traumatic brain injury patients

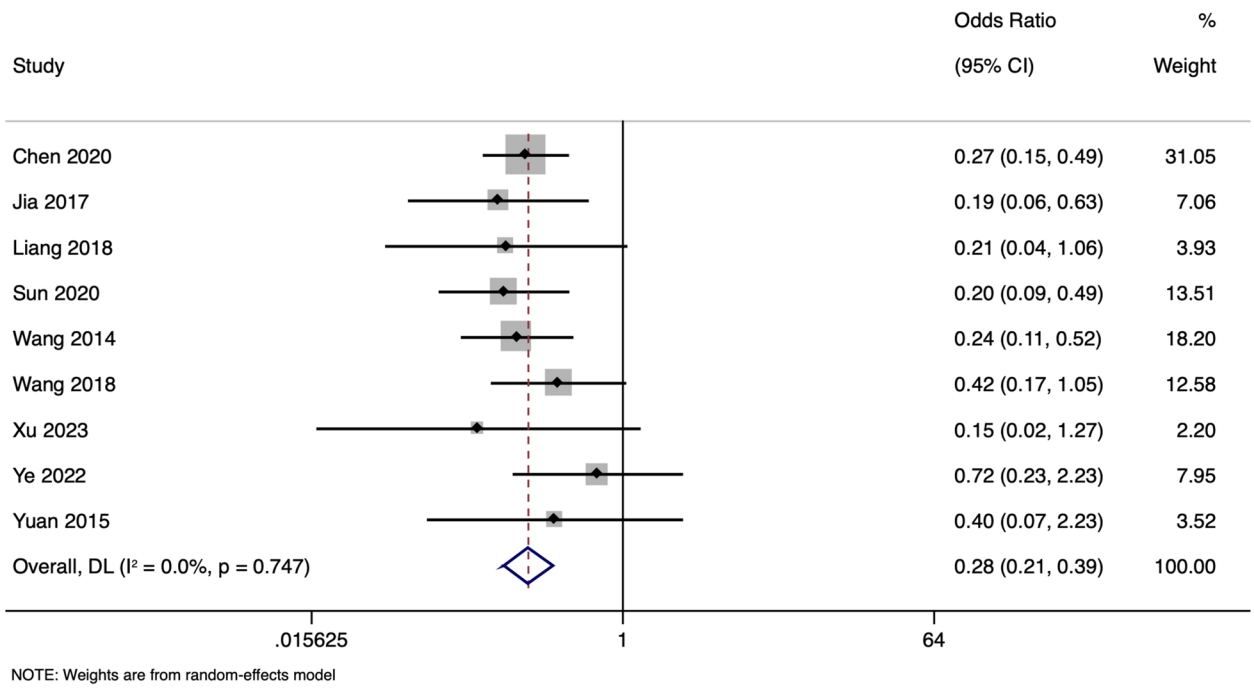


**Fig. 4** Forest plot comparing the effectiveness of controlled depression against conventional depression for cerebral infarction amongst severe traumatic brain injury patients

studies was absent, with a Cochran's Q statistic of 0.70 (p = 0.706), an H statistic of 0.590, and an $I^2$ of 0.0%, demonstrating consistency across the studies' findings. Sensitivity analysis excluding high risk of bias studies did not show significant difference in the pooled estimate (pooled OR = 0.57; 95%CI 0.34 to 0.94; n = 2).

#### Favourable GOS outcome

In this meta-analysis focusing on the impact of controlled decompression on GOS favorable outcomes in patients with severe traumatic brain injury, three studies with 398 participants were included. The analysis revealed a pooled odds ratio of 1.822 (95% CI 1.211 to 2.740, p = 0.004) using a random-effects

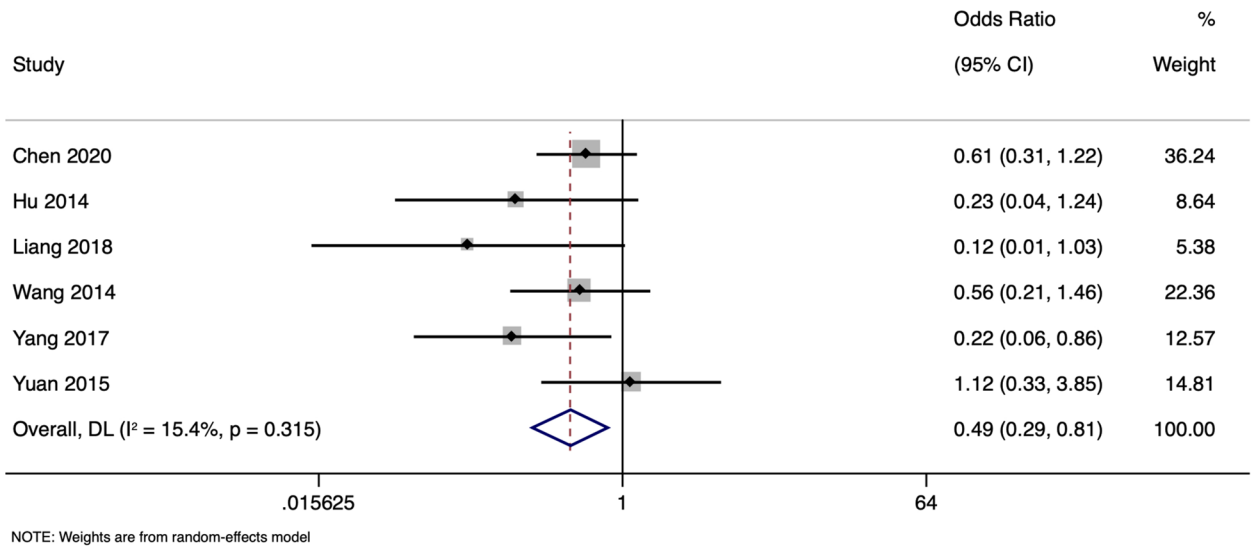


**Fig. 5** Forest plot comparing the effectiveness of controlled depression against conventional depression for brain swelling amongst severe traumatic brain injury patients

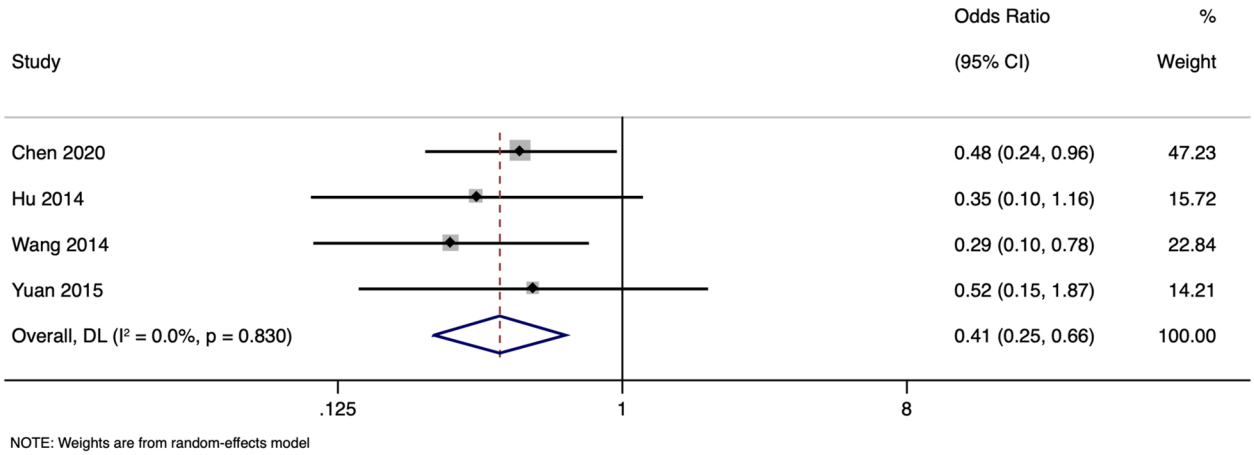


**Fig. 6** Forest plot comparing the effectiveness of controlled depression against conventional depression for delayed haematoma amongst severe traumatic brain injury patients

model, indicating a significant increase in the odds of favorable GOS outcomes with controlled decompression (Fig. 8). The heterogeneity among the studies was absent, demonstrated by a Cochran's Q statistic of 0.25 (p = 0.882), an H statistic of 0.354, and an $I^2$ of 0.0%, suggesting a consistent effect across the studies. Sensitivity analysis excluding high risk of bias studies did not show significant difference in the pooled estimate (pooled OR = 1.79; 95% CI 1.15 to 2.76; $n = 2$).

**Good prognosis**

This meta-analysis assessed the effect of controlled decompression on the prognosis of patients with severe traumatic brain injury, including three studies with a total of 248 participants. The pooled odds ratio, calculated through a random-effects model, was 2.488 (95% CI 1.292 to 4.792, $p = 0.006$), indicating a significant improvement in prognosis with controlled decompression (Fig. 9). The heterogeneity among the

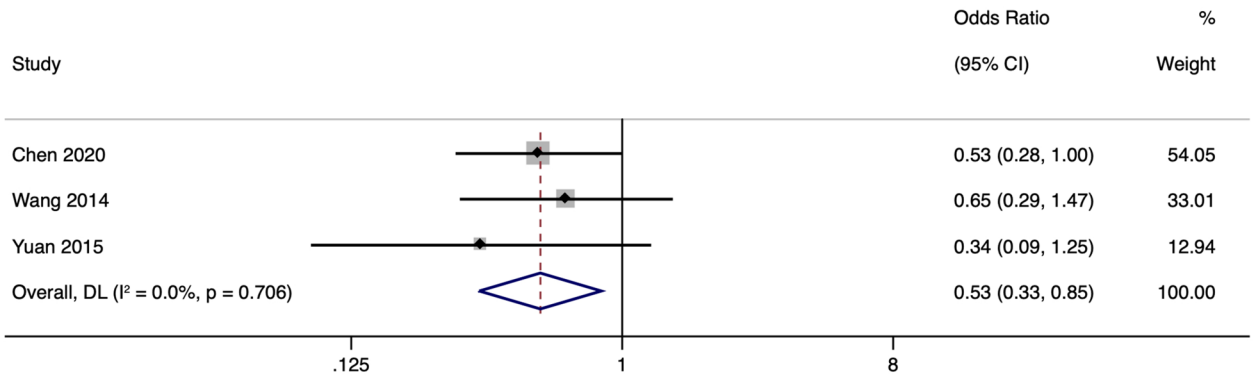


**Fig. 7** Forest plot comparing the effectiveness of controlled depression against conventional depression for favourable GOS outcome amongst severe traumatic brain injury patients

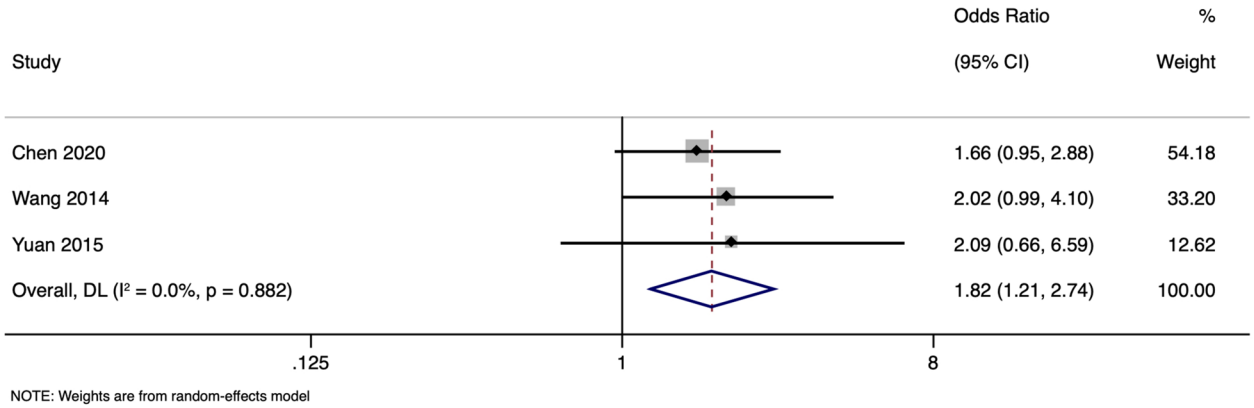


**Fig. 8** Forest plot comparing the effectiveness of controlled depression against conventional depression for prognosis amongst severe traumatic brain injury patients

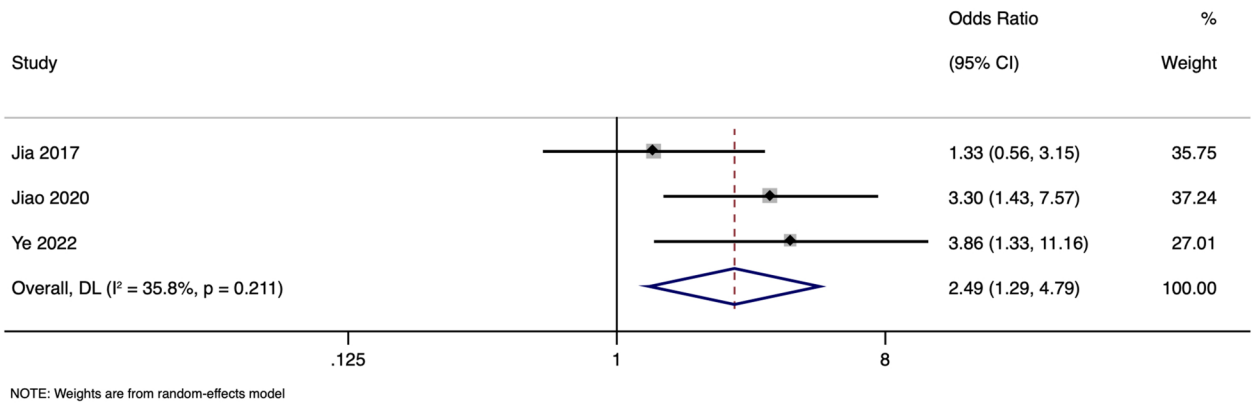


**Fig. 9** Forest plot comparing the effectiveness of controlled depression against conventional depression for total effective rate amongst severe traumatic brain injury patients

studies was moderate, with a Cochran's Q statistic of 3.11 ($p=0.211$), an H statistic of 1.248, and an $I^2$ of 35.8%, suggesting some variability in the effect sizes reported by the included studies. Sensitivity analysis was not possible as there was only one study without high risk of bias.

### Total effective rate

This meta-analysis investigated the total effective rate of controlled decompression compared to conventional methods in patients with severe traumatic brain injury, including only two studies with a total of 210 participants. The pooled odds ratio, utilizing a random-effects model, was 6.549 (95% CI 1.852 to 23.153, $p=0.004$), indicating a significant improvement in total effective rate with controlled decompression (Fig. 10). There was no heterogeneity between the studies, evidenced by a Cochran's Q statistic of 0.11 ($p=0.740$), an H statistic of 0.332, and an $I^2$ of 0.0%, indicating consistent findings across the included studies. Sensitivity analysis was not possible as none of the studies reporting this outcome were without high risk of bias.

### GRADE findings

Although there was no need to downgrade the quality of evidence based on indirectness—pertaining to the population, intervention, comparator, or outcome—or imprecision, as most confidence intervals were precise and did not cross the null effect (with the exception of the total effectiveness rate, which exhibited imprecise confidence intervals), or inconsistency (owing to negligible or no heterogeneity across all outcomes), the majority of the included studies were subject to some concerns or a higher risk of bias. This necessitated a downgrade in the quality of evidence to low.

## Discussion

This review rigorously evaluated the efficacy of controlled decompression versus conventional decompression techniques in the management of severe TBI across several critical outcomes, including mortality, postoperative complications, cerebral infarction, brain swelling, delayed hematoma, GOS favourable outcomes, prognosis, and total effective rate. Collectively, these findings suggest a significant benefit of controlled decompression in improving patient outcomes in several dimensions. Notably, the analysis demonstrated a substantial reduction in mortality (OR 0.498), postoperative complications (OR 0.283), and cerebral infarction (OR 0.488), alongside a significant decrease in brain swelling (OR 0.409) and delayed hematoma (OR 0.534). Moreover, it showed a marked improvement in favorable GOS outcomes (OR 1.822), prognosis (OR 2.488), and total effective rate (OR 6.549).

The findings from this review align with and extend the results of previous studies on the benefits of controlled decompression in severe TBI management [15–24]. Previous literature has similarly reported reductions in mortality and morbidity with advanced decompressive techniques, underscoring the potential for controlled decompression to mitigate secondary brain injury mechanisms [15–24]. However, this study distinguishes itself by its comprehensive scope, encompassing a broader range of outcomes and providing a more nuanced understanding of the intervention's efficacy.

The benefits observed with controlled decompression in severe TBI management are likely multifactorial, stemming from both direct and indirect effects of the intervention. Beyond the immediate goal of reducing ICP, controlled decompression facilitates a more nuanced management of cerebral blood flow and oxygenation [8]. This ensures that the brain's metabolic demands are met more effectively, even in the context

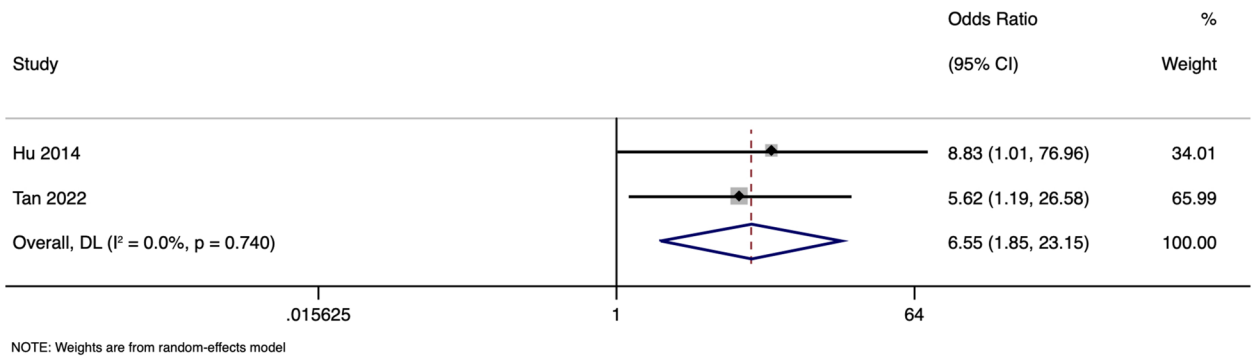


**Fig. 10** gvjkvvkjck kjcn, m

of injury, which could explain the significant improvements in outcomes like cerebral infarction rates and brain swelling. [25]

Controlled decompression may also exert a beneficial effect by modulating the inflammatory response following TBI [26]. Severe brain injuries are associated with a robust inflammatory reaction that can exacerbate tissue damage and contribute to secondary injury mechanisms [27]. By alleviating mechanical stress and improving blood flow, controlled decompression might reduce the propagation of inflammatory mediators and the extent of secondary brain damage [26]. This aspect of decompression's mechanism could be a critical factor in the observed reduction in mortality and improvement in prognosis.

Another potential reason behind the effectiveness of controlled decompression could be its neuroprotective effects [28]. By preventing severe episodes of intracranial hypertension, controlled decompression minimizes the risk of ischemic insults to the brain, which are a common cause of poor outcomes in severe TBI [28]. The prevention of these ischemic episodes helps preserve brain tissue and can facilitate recovery, contributing to the observed favourable outcomes, particularly in terms of GOS scores and overall prognosis.

Controlled decompression's ability to optimize cerebral perfusion pressure (CPP) is another vital factor contributing to its success [29]. CPP, the difference between mean arterial pressure and ICP, is crucial for ensuring adequate blood flow to the brain. Controlled decompression, by reducing ICP in a targeted manner, can help maintain or improve CPP without necessitating aggressive systemic blood pressure management. This optimization of CPP is essential for preventing both hypoperfusion and hyperperfusion-related damage, thereby improving overall neurological outcomes. [29]

Conventional decompression methods, while widely utilized, come with several inherent drawbacks that may limit their effectiveness in severe TBI management [20, 23]. Conventional decompressive craniectomy involves the immediate removal of a large bone flap to rapidly reduce ICP. Although this approach is effective in quickly lowering ICP, it can disrupt cerebrovascular autoregulation and increase the risk of complications such as brain herniation, subdural effusions, and hydrocephalus. Additionally, the abrupt release of pressure can lead to rapid shifts in cerebral structures, potentially worsening brain injury. [18–25]

Moreover, conventional methods are associated with higher incidence of cerebral infarction due to impaired cerebral perfusion and increased susceptibility to ischemic events. The lack of a stepwise or controlled approach to decompression may contribute to hemodynamic instability and impair the brain's ability to adapt to the sudden changes in pressure gradients. This can exacerbate secondary injury mechanisms, including neuroinflammation and excitotoxicity, resulting in poorer clinical outcomes. [20–23]

In contrast, controlled decompression techniques aim to overcome these limitations by gradually reducing ICP, allowing the brain to adapt to pressure changes more physiologically [8]. This progressive approach preserves cerebral perfusion, minimizes the risk of ischemic injury, and reduces the likelihood of secondary complications such as brain swelling and delayed hematoma. The reduced complication rates observed in our meta-analysis highlight the clinical benefits of this approach compared to conventional methods. Therefore, integrating controlled decompression into clinical practice may offer a more balanced and safer strategy for managing severe TBI, ultimately improving long-term outcomes. [26–29]

An important consideration in interpreting the findings is the methodological variability across the included studies. Differences in study design, patient selection criteria, and the operational definition of controlled decompression versus conventional methods could have influenced the outcomes. Some studies applied controlled decompression using stepwise intracranial pressure reduction protocols, while others utilized staircase decompression methods. Additionally, the timing and extent of decompression varied, potentially impacting the observed clinical outcomes. The diversity in outcome measurement tools and follow-up durations also poses challenges in drawing definitive conclusions. Recognizing these methodological differences is crucial for contextualizing the findings and identifying areas where future studies can adopt more standardized approaches to ensure comparability.

## Limitations of study

However, the study is not without limitations. The majority of included studies exhibited some concerns or a higher risk of bias, necessitating a downgrade in evidence quality. Additionally, the analysis of the total effective rate was based on a limited number of studies, highlighting a need for further research. Publication bias assessment could not be done as there was less than 10 studies across all the included outcomes (there were fewer than minimum number of studies to perform Funnel plot and Egger's test as per Cochrane guidance). Another significant limitation of our review is that all the included studies were conducted in China and involved Chinese patient populations. This geographical restriction may limit the generalizability of the findings to other regions and populations, as genetic, cultural, and healthcare system-related factors

could influence outcomes. The predominance of Chinese studies may reflect the local research focus and clinical interest in exploring alternative decompression techniques for severe TBI, possibly driven by the unique characteristics of patient populations or resource availability in China. The lack of studies from other regions suggests that controlled decompression may not yet be widely adopted or thoroughly investigated globally. It is also possible that clinical practice preferences, infrastructure availability, and differences in research priorities have contributed to this regional focus.

The findings underscore the potential of controlled decompression as a superior intervention in severe TBI management, suggesting it may offer a more favourable risk–benefit profile compared to conventional methods. These results have important implications for clinical practice, potentially guiding surgical decision-making and patient care strategies to improve outcomes in this critically ill population. The evidence supporting the efficacy of controlled decompression in severe TBI management suggests that it is time to consider integrating these findings into clinical guidelines. Developing standardized protocols that incorporate controlled decompression could facilitate its adoption across trauma centers, ensuring that patients benefit from the latest advances in care. These guidelines should be dynamic, incorporating new evidence as it becomes available and allowing for adjustments based on individual patient needs.

However, the decision to employ controlled decompression techniques involves complex ethical considerations, particularly in cases where the patient's prognosis is uncertain. Informed consent processes must adequately address the risks and benefits of these interventions, ensuring that patients or their legal guardians are well-informed decision-makers in their care. Furthermore, ethical guidelines should be developed to navigate the decision-making process in situations where the patient's wishes are not known, and surrogate decision-makers are involved.

While the benefits of controlled decompression are evident from this review, the comparative effectiveness of different decompressive techniques remains an area ripe for exploration. Future studies should aim to delineate the specific circumstances under which controlled decompression yields the most significant benefits. Additionally, identifying patient characteristics that predict a favorable response to controlled decompression could enhance patient selection criteria. These criteria may include, but are not limited to, age, severity of injury, time since injury, and specific injury patterns on neuroimaging. A personalized approach to decompression, based on a comprehensive understanding of these factors, could further improve outcomes for severe TBI patients.

Future research should aim to address the existing limitations by conducting high-quality, multicentre RCTs with larger sample sizes and longer follow-up periods. Studies should also explore the optimal timing, extent, and techniques of controlled decompression to refine clinical guidelines further. Additionally, research into patient-specific factors that may influence the effectiveness of controlled decompression could provide insights into personalized treatment approaches.

## Conclusion

This review provides compelling evidence of the benefits of controlled decompression over conventional methods in the management of severe traumatic brain injury. By significantly reducing mortality, postoperative complications, cerebral infarction, brain swelling, and delayed hematoma, while improving favourable GOS outcomes, prognosis, and total effective rate, controlled decompression emerges as a critical intervention in the treatment of severe TBI. Despite the need to downgrade the evidence quality due to study limitations, these findings highlight the importance of adopting controlled decompression techniques in clinical practice to enhance patient outcomes.

## Supplementary Information

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Supplementary Material 1.

Supplementary Material 2.

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**Author contributions**
XW and BZ contributed to the conception and design of the study, as well as the drafting and critical revision of the manuscript. LG and JS were responsible for data collection, analysis, and interpretation. GL provided expertise in statistical analysis and contributed to the final review and editing of the manuscript. All authors approved the final version of the manuscript and agree to be accountable for all aspects of the work, ensuring its accuracy and integrity.

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**Availability of data and materials**
No datasets were generated or analysed during the current study.

## Declarations

**Ethics approval and consent to participate**
Not applicable (as this was a systematic review of publicly available manuscripts).

**Consent for publication**
Not applicable.

**Competing interests**
The authors declare no competing interests.

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